HIGH TUNNEL PRODUCTION OF LETTUCE (*LACTUCA SATIVA)* AND SNAP BEANS (*PHASEOLUS VULGARIS* L.) IN A HIGH LATITUDE LOCATION

By

Heidi B. Rader

RECOMMENDED: ______________________________

____

____
Advisory Committee Chair

____
Chair, Department of Plant, Animal, and Soil Sciences

APPROVED: ______________________________
Dean, School of Natural Resources and Agricultural Sciences

____
Dean of the Graduate School

December 5, 2006
Date

HIGH TUNNEL PRODUCTION OF LETTUCE (*LACTUCA SATIVA)* AND SNAP

BEANS (*PHASEOLUS VULGARIS* L.) IN A HIGH LATITUDE LOCATION

A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

Heidi B. Rader, B.A.

Fairbanks, Alaska

December 2006

Abstract

Fairbanks, Alaska (lat. 64°49'N) has a short, variable, growing season which requires alternative growing techniques for reliable vegetable production. The efficacy of a high tunnel for season extension and yield improvements of lettuce (*Lactuca sativa*, 'Two Star' and 'Parris Island cos') and snap beans (*Phaseolus vulgaris* L., 'Concesa' and 'Provider') were evaluated in summers 2005 and 2006. Air/soil temperatures, relative humidity, and light penetration were monitored in a double bay high tunnel [15.8 m wide × 3.7 m high × 14.6 m long]. Mean temperature gains were 0.5 °C (air) and 1.2 °C (soil) in the high tunnel over two seasons. Lettuce was frost hardy in the open field, but prone to bolting in the high tunnel. The 3 Aug. 2005 'Two Star' planting ($P < 0.001$) was greater in the high tunnel but for some mid-season plantings of both cultivars, yield was greater in the field. The high tunnel protected snap beans from frost, wind damage, and low temperatures. 'Concesa' produced significantly more in the high tunnel compared with the field in 2005 and 2006 ($P < 0.005$). 'Provider', produced more in the high tunnel in 2006, but overall, yield improvements were not significant. Protection from rain and pests were other benefits of the high tunnel.

Table of Contents

Page

Page

List of Figures

Page

List of Tables

List of Appendices

Page

Acknowledgements

I would like to thank my major advisor, Dr. Meriam Karlsson, for funding for this entire study, assisting me in writing all aspects of this manuscript, and for publishing my first peer-reviewed journal article with me. I would also like to thank Jeffrey Werner, Research Professional, for help in developing this study and logistical support in all aspects of this study. I would like to thank all of my committee members for their support and guidance from helping me decide on a study topic to comprehensive exams to the actual thesis: Dr. Meriam Karlsson, Dr. Mingchu Zhang, and Dr. Jeffrey Smeenk. Thanks to the Agriculture and Forestry Experiment Station for assistance and a study site, and thanks to Terry Marsh, Research Associate, and all of the students who helped on the farm: Yosuke Okada, Cody Peterson, Mia Peterburs, Kalen Paul, and Wendy Langdon.

Chapter 1 General Introduction

Summary

Efficient and low cost technology such as high tunnels could have a dramatic effect on the economic viability of farms in high latitude locations such as Fairbanks, Alaska. Extended vegetable production in Alaska could decrease the need for produce to be shipped from trans-national and international sources, while improving direct market relationships and opportunities. A variety of plasticulture techniques are available that can trap these high radiation levels in the spring and increase air and soil temperatures for the purpose of season extension. High tunnels are temporary field structures in the shape of a Quonset-hut, covered with one layer of 6-mil plastic (Wells, 2004). They are a field plasticulture technique that allows routine activities such as weeding, ventilation, and harvesting to proceed with minimal additional labor (Lamont et al., 2003; Wells and Loy, 1993; Waterer, 2003). High tunnels provide protection from adverse weather conditions, pests, and low temperatures and can be used in conjunction with row covers, low tunnels, and plastic mulches.

High Tunnels

A high tunnel is defined as, "A portable walk-in, greenhouse-like structure without a permanent electrically powered heating or ventilation system, covered with one layer of plastic and sited on field soil." The High Tunnel Research and Education Facility (HTREF) established at Pennsylvania State University in 1999 uses 2.7 m high, 5.2 m wide x 11 m long high tunnels with initial construction costs of $ 1,900 per tunnel (Lamont et al., 2002a). Galvanized steel tubing (13 to 15 gauge) is covered with 4-year, greenhouse grade, 6-mil-thick, clear plastic. Sides are manually ventilated by rolling up the sides approximately 1 m. Drip irrigation is generally used in high tunnels, which is important for weed management, produce quality, and water use efficiency (Wittwer and Castilla, 1995). Temporary, propane heaters are sometimes used when episodic frosts are forecasted. High tunnels in Saskatchewan paid for themselves after two to five growing seasons with improved produce quality, decreased maturity times, and reduced damage from disease, insect pests, hail, rain (Waterer, 2003), and wind (Hodges and Brandle, 1996).

Low Tunnels, Row Covers, and Plastic Mulches

High tunnels should not be confused with low tunnels which are used over single rows and constructed out of wire hoops and plastic and might only be in place for the early growth stages of a crop. Some low tunnels are completely closed and then removed entirely after the early growth stages while some have an open slit that can be held open or closed with clothespins (Hall and Besemer, 1972).

Demonstrations in Palmer showed that row covers and low tunnels protected transplants and mature crops from wind, root maggots, and cold while increasing soil temperatures by 1.7 to 3.3 °C depending on design (Purser, 1996). Clear plastic mulches raised soil temperatures 4.4 to 5.6 °C compared with bare soil (Purser and Comeau, 1989). Other benefits were decreased maturity times of 7 to 21 d and 2 to 5 times as much yield for a variety of crops compared with bare soil (Purser and Comeau, 1990). Certain row covers, for example Reemay™ (a spun-bonded polyester) provide frost protection to -1.1 °C and 80% light transmission while allowing air and water penetration and eliminating the need for ventilation through perforation or slits (Purser, 1996). Perforated polyethylene did not provide frost protection (Purser and Comeau, 1989). Plastic mulch can be laid at the same time as the beds are formed, however row covers usually need to be manually laid and opened as needed for weeding, ventilation and harvest (Purser, 1996). Although low tunnels initially require a lower capital investment than high tunnels and may sufficiently increase yields and lengthen the growing season in some situations, their intensive labor requirements and limited frost protection can make them less profitable than high tunnels in some situations. It is also necessary to balance the goals of frost protection and higher night time temperatures versus preventing overheating during the day (Wells and Loy, 1985). High tunnels provide a way to achieve both of these goals without compromising because of the ability to ventilate and provide a temporary heat source.

History of Plasticulture

Tiberius Caesar (14 to 37 AD) first employed protected agriculture techniques with beds that could be moved inside when temperatures were too low (Dalrymple, 1973). The Romans also used clear sheets of mica or alabaster to protect the plants. England, Holland, France, Japan, and China experimented with a variety of protective structures from the 1500s to 1800s until the 19th century greenhouse structures similar to those used today were used.

Through the centuries, various agriculture technologies were employed to improve growing conditions, which included glass bells, clear paper covers, plastic mulches, low-tunnels, high tunnels, and fully regulated greenhouses (Wittwer and Castilla, 1995). Globally, glass greenhouse production stabilized at 37, 900 ha in the 1960s and has remained relatively constant. On the other hand, plastic greenhouse production has risen more significantly from the 1970s to the 1990s.

Along with changes in structures used, the types of crops grown have also changed. In the 19th century an estimated 1000 greenhouses in the United States were used for winter vegetable production. Later, 95% of greenhouse and tunnel space was used for bedding plants, potted plants, flowers, and ornamentals: only 10-20% of the bedding plants being vegetables. Ninety percent of Holland's protected production was vegetables in 1960 but is down to 40% now with flowers and ornamentals filling in the gaps. Low cost shipping often makes it cheaper to produce vegetables in warmer climates rather than using greenhouses.

Plastic structures make winter vegetable production in colder climates a more economically plausible option. At the University of Kentucky, Emmert (1955) used polyethylene film for row covers, mulches, and plastic covered greenhouses for vegetable production after its introduction in the U.S. following World War II and became known as the "Father of Plastics" (Hall and Besemer, 1972). The first plastic greenhouse was erected in 1953 at the Kentucky Agricultural Experiment Station (Lamont et al., 2003). Plastics allowed greater expansion of protected agriculture than glass because of their lower cost and higher versatility.

Geographic Usage of High Tunnels

Between 1970 and 1990, much of Europe and the Mediterranean saw a significant increase in high tunnel use (Wittwer and Castilla, 1995). In northern Europe, early fruit was worth up to four times more than fruit harvested during the main season which made protected agriculture economically viable (Hancock and Simpson, 1995). Use is somewhat dependant on local economics as well as competition from neighboring areas. Poland and Scandinavia produced strawberries without protected agriculture because it was not competitive with imported strawberries from other parts of Europe.

Although high tunnel use is minimal in the United States compared with Europe, the northeastern U.S. is seeing rapid growth (Wells and Loy, 1993). In New Hampshire in 1988, 15 high tunnels were in production, but by 1992, 80 high tunnels were used for vegetable production. The HTREF estimated that in 2002, after three years of operation, there were 350 new high tunnels constructed in Pennsylvania, largely in concert with the efforts of the High Tunnel Extension Program (Lamont et al., 2002b). Through there program 30,000 people learned about the benefits, economics, construction techniques, and maintenance issues of high tunnels. In the northern United States, use is primarily seasonal from early spring to fall (Wells and Loy, 1993). Although Penn State is one of the largest research facilities, universities across the lower 48 are conducting research on high tunnels. In North America, high tunnel research at high latitudes is limited to the University of Saskatchewan and research farms in Palmer and Fairbanks, more recently. In 2006, there was only one known commercially sized high tunnel in the Fairbanks area. As high tunnel popularity expands, it will be more important to have relevant management, cultivar, and crop recommendations.

High tunnel vegetable production in Europe is considerably higher than North America (Wells and Loy, 1993). Lower transportation costs, lower food prices, centralized marketing systems, and reluctance to pay more for high quality, fresh produce in the United States may contribute to this disparity (Hancock and Simpson, 1995). As fossil fuel prices and awareness of sustainable agriculture increases (Andersen, 2004; Horne and McDermott, 2001), high tunnel vegetable production in the United States may become more prevalent.

Benefits of High Tunnels

High tunnels can lengthen the growing season, increase yields, improve quality, and increase supply reliability, primarily due to higher temperatures (Lamont et al., 2003; Waterer, 2003; Wells and Loy, 1993; Wittwer and Castilla, 1995). These qualities could be especially helpful for villages in Alaska which are isolated from fresh produce by high shipping costs. In New Hampshire, high tunnels extended the growing season one to four weeks in the spring and two to eight weeks in the fall (Wells and Loy, 1993). Faster soil warming is important for decreasing maturity times (Lamont et al., 2003). High tunnels in Saskatchewan provided 2 °C frost protection (Waterer, 2003). Higher and more reliable yields were achieved all summer when ventilation was performed as field temperatures reached 30 °C.

Although temperature is usually the most important environmental factor affecting growth in high tunnels, there are several other significant factors. Shelter from the wind is another beneficial property of high tunnel field production (Hodges and Brandle, 1996; Wells and Loy, 1993; Wittwer and Castilla, 1995). Wind increased transpiration rates, lodging rates, and nutrient loss while it decreased crop growth, photosynthetic efficiency, and pollination rates (Hodges and Brandle, 1996). Wind stressed plants were smaller and more compact with a higher root to shoot ratio than sheltered plants (Biddington, 1985). Some of these effects are directly caused by wind while some are due to influences on the microclimates.

Yields improved in sheltered areas by 5% to 50%, especially early in the spring during plant establishment (Hodges and Brandle, 1996). Snap beans, an indeterminate crop, produced 37% higher yields when plastic windbreaks were used (Bagley and Gowen, 1960) which could be because even small gusts of wind can damage sensitive crops (Finch, 1988). In Fairbanks, seedlings are often established in heated greenhouses and then transplanted to the field. High tunnels could make direct seeding possible by protecting seedlings from the wind.

Shelter from rain and hail in high tunnels increased the quality and reliability of produce (Wittwer and Castilla, 1995; Wells and Loy, 1985). Reduced moisture on leaves could prevent diseases such as late blight (*Phytophthora infestans*) which proliferates in cool, moist environments in Alaskan potatoes (Jahns, 2005). Shelter from rain can also improve cleanliness of head lettuce and baby salad greens. High tunnels also improved quality of cut flowers (Lamont et al., 2003) which degrade quickly with hard rains and hail. Cut flower production may be an especially important crop for high tunnels because their marketability is easily destroyed by hail or rain storms and events such as weddings require reliable supplies.

High tunnels helped maintain an insect and pest free environment (Lamont et al. 2003, Wells and Loy, 1985, Wittwer and Castilla, 1995). Over three growing seasons, Waterer (2003) had minimal problems with disease and insect pests in high tunnels and used no pesticides. When high tunnels are used in warmer, more humid areas, for longer seasons; disease and infestations may be more problematic (Lamont et al., 2003). The green peach aphid (*Myzus persicae*) and the greenhouse whitefly (*Trialeurodes vaporariorum*) were the primary insect pests in Pennsylvania; at the HTREF, biological control, insect scouting, and good sanitation were the primary mechanisms for disease control which limited pesticide and fungicide use.

High tunnels are usually drip-irrigated; this precise watering significantly reduced weeds in the areas between rows (Lamont et al., 2003; Waterer, 2003; Wells and Loy, 1993). This is important as the optimal growing temperatures in high tunnels can also benefit weed populations, but insufficient water decreased weeds (King and Oliver, 1994). High tunnels provide easy access for mechanical removal of weeds as compared with low tunnels, which may require higher rates of herbicides (Wells and Loy, 1993). High tunnels provide weed management options that are less cumbersome than other plasticulture techniques.

High Tunnel Growing Environment

High tunnels are usually not heated or ventilated automatically so the growing environment is highly dependent on management. Penn State high tunnels recorded average gains of 5 °C, but gains of 8 to 28 °C were also recorded depending on ventilation (Burkhart and White, 2003). Without ventilation, temperatures could increase at a rate of 6.7 $°C \cdot h^{-1}$ in the tunnel. Differences between field and tunnel temperatures are also dependent on season, time of day, sky cover, and wind. Relative humidity was similar in the high tunnel and in the field with averages between 80% to 90% at night and 30% or lower during the day. Relative humidity in the tunnel was 4% to 7% higher near the sides of the tunnel than the middle of the tunnel. Polyethylene plastic transmitted about 90% of photosynthetic photon flux density (PPFD) (Wells and Loy, 1993).

Type of Produce Grown

A wide variety of vegetables, herbs, fruits and flower crops have been grown successfully in high tunnels (Lamont et al., 2003). Traditionally, cucumbers, tomatoes, and strawberries have been the most popular greenhouse crops, but the earlier maturity and higher quality produce achieved in high tunnels can compensate financially for lower value crops (Wittwer and Castilla, 1995). In Saskatchewan higher yields of muskmelon, pepper, and tomatoes were achieved when grown in high tunnels as opposed to low tunnels (Waterer, 2003). Salad is often grown in greenhouses in northern Europe, Japan, Russia, Poland, and Hungary while very little greenhouse salad is grown in the U.S. (Wittwer and Castilla, 1995). Snap beans are grown using protected agriculture in some Mediterranean countries as well as China.

While it is important to evaluate crops based on their value and general temperature requirements, cultivars should also be screened for favorable responses to high tunnels (Wells and Loy, 1985). For example, certain types of lettuce were more prone to bolt in high tunnels than other types (Zhao et al., 2003). Crops with similar temperature requirements should be grown together in a high tunnel so that ventilation and heating practices optimize yields of all crops (Waterer, 2003). Different cultivars should be screened in different geographic areas to account for unique, climactic conditions.

Economics of High Tunnels

Start up and operation costs are significantly lower for high tunnels than for commercial greenhouses. For prices in 1991, it cost \$13.56$\cdot$m^{-2} to construct a 4.3 × 29 m high tunnel, including labor (Wells and Loy, 1993), while start up costs for a fully automated quonset-hut shaped greenhouse in 1990 were \$24.80$\cdot$m^{-2} for an 8.5 x 28.9 m greenhouse (Healy et al., 1991). Automated greenhouses have additional costs from taxes, fuel for heating and electricity for ventilation, and higher labor costs for planting and other management procedures. High tunnels are not taxable, they are usually not heated and are manually ventilated, and can be tilled using a tractor. Michael Orzolek (HTREF) calls high tunnels, "Economic Development Units" because in Pennsylvania they have been used to produce a wide variety of horticulture crops throughout the year with a low initial capital investment (Wall et al., 2000). Waterer (2003) found that although high tunnels initially cost more than low tunnels, after two to five growing seasons, high tunnels generally paid for themselves. Materials, installation, and maintenance over a 3 year period for high tunnels cost \$13.25/linear m of row and low tunnels cost \$0.46/linear m of row. Peppers had a higher gross return than tomatoes or muskmelon when grown in high tunnels because they ripened to red which is a significantly higher value than green fruit. In Florida, early strawberries were priced four times higher than later strawberries, making season extension profitable (Hochmuth et al., 1993). During the early growing season of Fairbanks, lettuce could be sold for \$2.00/head while mid-season when supply was high, lettuce might sell for \$1.00/head (G. Kerndt, personal communication). Snap beans could be sold for up to \$4.50·lb.$^{-1}$, but commonly were sold for \$3.00·lb.$^{-1}$ and sometimes were sold for as little as \$1.50·lb.$^{-1}$ when supply was high (P. Mayo, G. Kerndt, J. Powalski, personal communication). In general, higher supplies during the middle of the summer bring prices down.

There are a variety of costs specific to high tunnels including labor and infrastructure. Fixed costs for a 17 × 96 ft. high tunnel were calculated to be \$ 580.23 per season for land, structure, and machinery and equipment; ventilation and monitoring labor \$ 275.00 for the season (Harper, 2003). Fixed costs for a 14 × 96 ft. high tunnel were \$478.49 per season with the structure considered to be a 10 year investment and the plastic a 3 year investment (Appendix A). The cost of a temporary heat source was not calculated, but would add an additional cost.

Case Study: Tomatoes

In Alaska, tomatoes are a popular, high value, fresh market crop, in part because they are commercially only grown in greenhouses (Matheke et al., 2006). Several tomato cultivars show some potential in Fairbanks for ripening in field production, depending on growing season conditions. At \$4.00·lb.$^{-1}$, tomato production is a worthwhile investment in the area and may be considerably more profitable if lower cost plasticulture techniques such as high tunnels were used rather than fully automated greenhouses (personal observation at the Tanana Valley Farmer's Market, 26 July 2006). Greater ventilation and thus higher insect pollinators in high tunnels compared with automated greenhouses may decrease the need for daily, manual pollination. A back-up heat source could prevent frost damage and cold injury which is not an option with field production, low tunnels, or row covers.

Yield Comparisons: High Tunnel, Low Tunnel, and Open Field[1]

In Fairbanks, three cold hardy tomato cultivars produced more than 4.0 lb.·plant^{-1} in the open field with IRT-100 wavelength plastic mulch for soil warming and weed control (Matheke et al., 2006). Depending on the growing season, the same cultivars produced as little as 1.5 lb.·plant^{-1} and as much as 8.6 lb.·plant^{-1}. In Saskatchewan, Canada, Waterer (2003) found that high tunnels produced 12.8 lb.·plant^{-1} while low tunnels produced 6.6 lb.·plant^{-1} with plastic mulch used in both locations as well. In Pennsylvania, tomatoes in high tunnels produced from 4.7 to 2.7 lb.·plant^{-1} depending on cultivar (White and Orzolek, 2003). With average cold hardy production rates in

---

[1] Yields were converted to lb.·plant^{-1} for the sake of comparison even if yields were reported in other units.

Fairbanks, a yield of 960 lb.·season^{-1} in a 14 × 96 ft. high tunnel would be reasonable, especially given the added frost and cold protection. At \$4.00·lb.$^{-1}$, annual net returns were calculated to be \$1,293.11, using Sciabarrasi and Wells (1999) economic analysis. If high tunnel yields were double that of the field (with mulch) as high tunnel yields in Saskatchewan doubled over low tunnel production, annual returns of \$4,509 could be expected for a 14 × 96 ft. high tunnel.

As land prices increase, fossil-fuel becomes more expensive, and people are more willing to pay for fresh local produce, high tunnels should become more economically viable (Wittwer and Castilla, 1995). High tunnels efficiently use land, water, sunlight, energy, and atmospheric CO_2. Aberrant weather events have less impact, especially early and late frosts; direct market opportunities could increase early and late in the season when the overall supply of local produce is lower (Gent, 1991, Lamont et al., 2003, Wells, 1991). A more reliable supply for direct markets is beneficial for the farmer as well as the consumer (Ross et al., 1999; Safley et al., 2004; Wells and Loy, 1993). High tunnels provide similar benefits as greenhouses without relying on costly fossil-fuels for ventilation and heating.

Future of High Tunnels

High tunnel use in the U.S. is relatively new which leaves a significant amount of research to be done (Lamont et al., 2003; Wittwer and Castilla, 1995). It is important to identify appropriate cultivars for various geographic locals as well as cultivars that are appropriate for local markets. Management practices should also be researched according to climate. Alternative ways of managing the high tunnels include thermo-reflective screens (Polysack plastic industries, Nir Yitzhak, D.N. Negev Israel) which are placed above crops during the afternoon and removed in the morning. Removable propane heaters also may prove beneficial for frost protection. Solar power was used to mechanically open the sides of the high tunnels when a certain temperature was reached; this makes logical sense because high temperatures are often present during high sunlight (Bachmann, 2005). Plastic mulches and row cover techniques can be used in conjunction with high tunnels when low temperatures persist. Along with plasticulture research, environmentally friendly methods of plastic disposal should also be developed. Opportunities for high tunnels are vast in Alaska and could be an important way to improve local agriculture production.

Lettuce (*Lactuca sativa*)

Although a cool season crop, lettuce (*Lactuca sativa)* is sometimes grown in greenhouses in the U.S. and Europe (Bierhuizen et al., 1973; Wien, 1997), but the majority of 78,000 acres of leaf lettuce production in the U.S. occurs in California (81%) and Arizona (16%) (USDA, 2004). In California, 64% of leaf lettuce production was Romaine, and 21% was green leaf (Kurtz, 2001). New cultivars have expanded the range of growing conditions for lettuce, especially in warmer areas and glasshouses (Bierhuizen et al., 1973). When water and nutrients are sufficient, light and temperature are the most important environmental factors affecting lettuce growth; their effect depending on duration, intensity, and timing (Wurr et al., 1981). Although lettuce is a cool season crop, some modern cultivars are resistant to bolting in warmer environments such as greenhouses (Wien, 1997). Greenhouse and controlled environment studies have made it possible to isolate light, day length, and temperature as they affect the growth and morphology of lettuce.

Light

At very low photosynthetic photon flux (PPF), net photosynthesis is negative because CO_2 efflux from dark respiration dominates CO_2 uptake (Gijzen, 1995). At slightly higher PPF levels, the rates of ATP and NADPH production in the light reaction limit regeneration of ribulose biphosphate which is needed for carboxylation. So photosynthesis is highly responsive to light and increases at a fairly linear rate until saturation is reached. This occurs when Rubisco activity becomes the limiting factor rather than ATP and NADPH. In one study, after butterhead lettuce achieved a weight of 60 g, fresh weight increased rapidly in response to increased radiation (Bierhuizen et al., 1973).

Mattei et al. (1973) demonstrated that lettuce was saturated by levels of radiation at: 250 $cal \cdot cm^{-2} \cdot day^{-1}$ (estimated to 555 $\mu mol \cdot s^{-1} \cdot m^{-2}$); while levels of 450 $cal \cdot cm^{-2} \cdot day^{-1}$ (estimated to 999 $\mu mol \cdot s^{-1} \cdot m^{-2}$) and above, inhibited growth. Dry mass and leaf number correlated positively with PPF while shoot to root dry mass ratio, specific leaf area, and length of hypocotyls in young lettuce transplants was negatively correlated with PPF (Kitaya et al., 1998).

Dennis and Dullforce (1974) observed bolting predispositions in young lettuce exposed to high radiation levels and long days. Lower irradiance increased time to maturity, while higher irradiance increased dry weights and decreased heading time. Lettuce used light most efficiently during the shortest day length (8 h) and at the lowest irradiance level of 2.8 klux (estimated to 50 $\mu mol \cdot s^{-1} \cdot m^{-2}$). Dry mass increased from 25% to 100% when exposed to 24 h days compared with 16 h days (Kitaya et al., 1998). However, production time was inefficient, necessitating 60 d as opposed to 14 d with a radiance of 17 klux (estimated to 315 $\mu mol \cdot s^{-1} \cdot m^{-2}$). Klapwijk (1979) also found that crop growth rates were reduced with lower radiation, but not proportionally as lower light was used more efficiently than higher light. At a constant temperature, 70% of the variability in young lettuce was attributed to differences in radiation. Low PPF levels resulted in satisfactory growth when day temperatures were 19 °C and night temperatures were 5 °C; higher temperatures did not provide additional benefits for 'Montana', a butterhead variety (Hicklenton and Wolynetz, 1987).

Temperature

Crops have different optimum curves for net photosynthesis and temperature (Gijzen, 1995). At lower temperatures, assimilation increases with temperature because of increased activity in the light reaction and carboxylation, but dark respiration and photorespiration also increases, which decreases net CO_2 uptake. When the optimum temperature has been exceeded, net photosynthesis is decreased. High temperatures cause light reactions to be less efficient and enzyme activities to decrease. Optimum temperatures for leaf lettuce production are 23 °C day/7 °C at night, while 28 °C day/12 °C night or above precipitates bolting, bitterness, tipburn, and poor heading (Jackson et al., 1996)

Temperature effects on lettuce production vary widely depending on growth stage and cultivar. Temperature influenced early growth stages most, but once 100% soil cover was reached, light was more important for leaf development and maintenance respiration (Bierhuizen et al., 1973; Challa, 1990; Pearson et al., 1997). High tunnels could be managed so that temperatures were higher during early growth stages of seeded or transplanted lettuce and full canopy expansion could take place more quickly. High temperatures overall and during the hearting period often led to leaf unfolding, sudden stem elongation, and thus bolting (Nothmann, 1977a). Otherwise, leaf production generally increased with temperature. Lettuce was also sensitive to bolting when propagated with temperatures of 16 °C as opposed to 20 °C (Dennis and Dullforce, 1974). Instantaneous temperature effects on photosynthesis showed that with a low irradiance, CO_2 uptake did not increase above 2 °C and with a higher irradiance, maximum photosynthetic rates were achieved at 10 °C (Lorenz and Wiebe, 1980). Since dry-matter production requires higher temperatures than CO_2 uptake, photosynthesis is not an appropriate means of temperature control for plasticulture. In another study, a low temperature of 12 °C limited dry matter accumulation and produced low specific leaf area values, while higher temperatures resulted in greater partitioning of dry matter to leaves (Hicklenton and Wolnetz, 1987). Above 20 °C, leaf area increased but head formation was prevented. A survey of regional climactic data indicated that, 23 °C was the optimum day temperature while 7 °C was the optimum night temperature, and optimum greenhouse conditions were 18 °C day/12 °C night (Kimball et al., 1967).

Raised soil temperatures in high tunnels could benefit spring lettuce crops but may harm summer crops (Jenni et al., 2003). Nothmann (1977b) found that heading and growth was poor at 28 °C and 36 °C, while heading was best at 12 °C although it delayed growth. Increased soil temperatures accelerated inner stem elongation and increased leaf twisting, while head height, head weight, and leaf size decreased. Increasing root temperatures from 20 to 29 °C minimally increased the plant size of the cultivar 'Montana,' a butterhead variety (Hicklenton and Wolynetz, 1987). Soil warming decreased maturity time by 8 to 11 d at 12.8 °C and 14 to 17 d at 18.3 °C (constant air temperature at 7.2 °C) (Boxall, 1971).

In hydroponic lettuce production, Hicklenton and Wolynetz (1987) found that an increase in day temperature from 12 °C to 23 °C led to an increase in fresh and dry weight at final harvest but an increase in night temperatures had limited effect. Costs of greenhouse production could be reduced by decreasing the air temperature during the dark period. It may be most economically efficient to induce a higher temperature in a glasshouse early until 100% soil cover is reached followed by a lower temperature because then radiation is more important (Bierhuizen et al., 1973).

Seasonal Fluctuations in Light and Temperature

Nothmann (1977a) found consistent heading, slow growth, and some leaf twisting in the spring which had increasing temperatures, radiation, and day length. During the summer, high temperatures and radiance led to rapid growth but low quality heads that were soft and open with limited leaf folding. The decreasing temperatures, radiation and day length of fall resulted in rapid growth at first, then decreased growth rate and some leaf folding. The ratio of light to temperature is much higher in the spring than in the autumn so this may play a role in bolting and growth (Bierhuizen et al., 1973). Lettuce crops grown in the fall used light two to three times more efficiently than those grown in the spring (Glenn, 1984). Winter had slow early growth, late heading but minimal bolting overall. Lettuce planted from May to June took about 40 d to mature while December crops took 62 d to mature.

High tunnels may be an important way to increase high latitude lettuce production. Earlier maturity, greater yield, and higher quality heads were grown using plasticulture in Quebec (Jenni et al., 2003). Effects of high irradiance and long day lengths during mid-summer should be considered as higher temperatures may have a negative impact on some lettuce cultivars. Cultivars for high tunnel production should be evaluated for bolting tolerance in response to higher temperatures and varying radiation levels and day length. Fall and spring will likely bring the most profit because of lower supply and higher market prices (Lamont et al., 2003; Waterer, 2003). Higher quality and a reliable supply in using high tunnels may make them important throughout the summer.

Snap beans (*Phaseolus vulgaris* L.)

Snap beans (*Phaseolus vulgaris* L.) are one of the most widely consumed green vegetables and are an important source of protein (Laing et al., 1984). Wide variation in growth habit, size of seeds and pods, temperature tolerance, and phenology make snap beans adaptable to a range of climates and growing environments such as high tunnels. Breeding histories could be important for selecting appropriate varieties for high tunnel growing environments in certain geographic areas. In general, snap beans are a warm-season crop although cultivars adapted for adverse conditions may not respond to higher temperatures (Davis, 1997). Snap beans have a low tolerance for frost, wind, and soil abrasion (Finch, 1988) and rain can cause blossom drop (Aguiar et al., 1998). Higher quality snap bean varieties sometimes achieved lower yields (Davis, 1997). Varieties with extra-fine pods (<6.5 mm diameter), considered higher quality, produced 25% to 30% less than varieties with very fine (6.5 to 8.0 mm diameter) and fine (8.0 to 10.5 mm) pods.

Snap beans are grown in a wide range of climates including northern Europe, North America, and the tropics (Laing et al., 1984). Although snap beans are primarily produced in Florida in the U.S., other seasonal produces are S. Carolina, N. Carolina, and Georgia in the spring, New York, New Jersey, N. Carolina, and Virginia during the summer, and Florida and Virginia during the fall. With proper cultivar selection, high tunnels could broaden the geographic range and seasons possible for profitable, snap bean production.

Light

Some cultivars have been bred to be photoperiod insensitive (Davis, 1997) which is important for high latitude areas with exceptionally long days. At the Centre Internacional de Agricultura Tropical (CIAT, 1980), out of 800 germplasms surveyed, 41% were insensitive to long days (18 h compared with 12 h) (Laing et al., 1984). Photoperiod sensitive cultivars took considerably longer to flower when exposed to long days than photoperiod insensitive cultivars. In Cambridge, Zehni et al. (1970) found longer photoperiods caused flower bud abscission. When photoperiod insensitive plants were exposed to increased temperatures, the days to flowering were reduced (Davis, 1997), but short-day plants took longer to flower when exposed to increased temperatures (Enriquez, 1975).

Temperature

Optimum germination temperatures were 25 °C (Aguiar et al., 1998) and 29 °C to 34 °C, depending on the cultivar, with no emergence below 8 °C (Davis, 1997) or even 15 °C (Balasubramanian et al., 2003). In Latin America, 80% of bean production occurred in microregions with average temperatures between 17.5 ° and 25 °C (Inoue and Suzuki, 1959; Laing et al., 1984) and 18.3 ° to 29.4 °C was identified as optimal plant growth temperatures (Aguiar et al., 1998). The optimum flowering temperature was 21 °C (CIAT, 1980). In most crops, photosynthetic rates increase up to 25 °C and then level off or decline (Jones, 1971). In snap beans, temperatures above 32 °C caused blossom and ovule abscission (Kigel et al., 1991, Aguiar et al., 1998). High tunnels could be managed to optimize temperatures for snap bean production to provide a longer growing season in high latitude areas.

Cold temperatures negatively impacted snap beans throughout their phenology (Dickson and Boettger, 1984) by reduced leaf net photosynthesis, transpiration rates, stomatal conductance, and electron transport (Penavaldivia et al., 1994). In Saskatchewan, suboptimal temperatures delayed germination and emergence of dry beans but were not permanently injurious. (Balasubramanian et al., 2003). Immediate effects of suboptimal temperatures on germination and emergence are often the focus of research, but cumulative effects are important as well. In field experiments, it was difficult to separate whether the causation of chilling injury was from raw temperature values or duration of exposure (Herner, 1986). For the cool, continental climates of the Canadian prairie, Kemp (1978) tested cultivars that had high tolerance for low temperatures through emergence, flowering, and seeding.

Relative growth rates were 2.5% per day at 10 °C and 10% per day at 15 °C (Austin and Maclean, 1972). Hodges et al. (2004) found that wind sheltered snap beans produced an average of 71% greater yield than non-sheltered beans, which was in part due to increased soil temperatures from 1 to 4 °C in sheltered areas. Varieties with large seeds and/or large cotyledons were more cold tolerant and produced earlier, more vigorous yields than small seeded cultivars, but they were often less palatable (Austin and Maclean, 1972; Kemp, 1978). With a small increase in temperature, high tunnels could decrease days to maturity and make cultivation of higher quality varieties possible.

High tunnels have the potential to heat up quickly when not ventilated, temperatures of 54 °C were recorded in a closed tunnel in central Pennsylvania (Burkhart and White, 2003). Snap beans with some heat tolerance may be desirable, although tradeoffs should be considered. Yields increased with temperatures up to 30.9 °C in heat tolerant lines, while heat susceptible lines had increased yields up to 23.8 °C (Rainey and Griffiths, 2005). However, heat tolerant genotypes were dwarfed and had lower biomass which made them less competitive with weeds. Higher temperatures increased branching (32 °C day/27 °C night) which increased flowering but any benefits from this were counteracted by flower and pod abscission (Kigel et al., 1991). Branching and flowering patterns were rigid compared with pod production which was highly responsive to environmental stresses. One cultivar studied, Hystyle, had low yield potential overall but consistently yielded under heat stress (Rainey and Griffiths, 2005). Tradeoffs are important considerations when breeding for high yield potential and non-optimal temperature extremes that may be present in high tunnels.

A significant amount of research has been done on cold tolerance (Austin and Maclean, 1972; Dickson and Boettger, 1984; Herner, 1986; Hume and Jackson, 1981; Kemp, 1978) and heat tolerance (Monterroso and Wien, 1988; Rainey and Griffiths, 2005; Weaver et al., 1985) in snap beans in growth chambers, greenhouses, and fields. High tunnels without backup heat do not offer significant protection from frost and without ventilation can heat up quickly. Cultivar selection for high tunnels depends on if the cultivar will be planted in the early season, mid-season, or the late season and whether or not temporary heat sources are used when frosts are expected to occur. Screening for cultivars that do well in high tunnels is important because those conditions are significantly different than those experienced in the field or in greenhouses. It is important to consider whether or not selecting cultivars based on cold or heat tolerance compromise yield and quality under optimal conditions. Knowledge of local market use, management decisions, and local climates needs to be the driving force for cultivar selection.

Literature Cited

Aguiar, J., F. Laemmlen, A. Baameuer, and K. Mayberry. 1998. Snap bean production in California. Division of Agriculture and Natural Resources Publication 7240 University of California Davis. 11 July 2006. <http://anrcatalog.ucdavis.edu/pdf/7240.pdf>.

Andersen, A. 2004. Women and sustainable agriculture: Interviews with fourteen agents of change. McFarland and Company, Jefferson, North Carolina.

Austin, R.B. and M.S.M. Maclean. 1972. A method for screening *Phaseolus* genotypes for tolerance to low temperatures. J. Hort. Sci. 47:279-290.

Bachmann, J. 2005. Season extension techniques for market gardeners. National Sustainable Agriculture Research Service ATTRA Publication IP035. 2 June 2005. <http://attra.ncat.org/attra-pub/seasonext.html>.

Bagley, W.T. and F.A. Gowen. 1960. Growth and fruiting of tomatoes and snap beans in the shelter areas of a windbreak. Proc. 5th World Forestry Congr. 3:1667-1670.

Balasubramanian, P., A. Vandenberg, and P. Hucl. 2003. Planting date and suboptimal seedbed temperature effects on dry bean establishment, phenology and yield. Can. J. Plant Sci. 84:31-36.

Biddington, N.L. 1985. A review of mechanically induced stress in plants. Scientific Hort. 36:12-20.

Bierhuizen, J.F., J.L. Ebbens, and N.C.A. Koomen. 1973. Effects of temperature and radiation on lettuce growing. Neth. J. Agr. Sci. 21:110-116.

Boxall, M.I. 1971. Some effects of soil warming on plant growth. Acta Hort. 22:57-65.

Burkhart, E.P. and L.D. White. 2003. The high tunnel cropping environment: understanding how things work, p 45-56. In: W. Lamont, M. Orzolek, and L. White (eds.). High tunnel production manual. Center for Plasticulture, Department of Horticulture, College of Agriculture, Pennsylvania State University.

Centre Internacional de Agricultura Tropical (CIAT). 1980. Bean Program Annual Report 1979. Cali, Colombia.

Challa, H. 1990. Crop growth models for greenhouse climate control, p.125-145. In: R. Rabbinge, J. Goudriaan, H. Van Keulen, F.W.T. Penning de Vries and H.H. Van Laar (eds.). Theoretical production ecology: reflections and prospects. Simulation Monographs 34. Wageningen Press, Wageningen, The Netherlands.

Dalrymple, D.G. 1973. A global review of greenhouse food production. U.S. Dept. Agr., Economic Research Service, Report 89, Washington, D.C.

Davis, J.H.C. 1997. *Phaseolus* beans, p. 409-428. In: H.C. Wien (ed.). Vegetable Crop Physiology. CAB International.

Dennis, D.J. and W.M. Dullforce. 1974. Analysis of the subsequent growth and development of winter glasshouse lettuce in response to short periods in growth chambers during propagation. Acta Hort. 39:197-218.

Dickson, M.H. and M.A. Boettger. 1984. Emergence, growth, and blossoming of bean (*Phaseolus vulgaris*) at suboptimal temperatures. J. Amer. Soc. Hort. Sci. 109(2):257-260.

Emmert, E.M. 1955. Results of research in 1955. 68th Annual Report, Kentucky Agriculture Experiment Station.

Enriquez, G.A. 1975. Effect of temperature and daylength on time of flowering in beans (*Phaseolus vulgaris* L.). Ph.D. diss. Cornell University, Ithaca.

Finch, S.J. 1988. Field windbreaks: design criteria. Agr. Ecosystems Environ. 22/23:215-228.

Gent, M.P.N. 1991. High tunnels extend tomato and pepper production. The Conn. Agr. Expt. Sta., New Haven. Bul. 893.

Gijzen, H. 1995. CO_2 uptake by the crop, p. 16-34. In: J.C. Baker, G.P.A. Bot, H. Challa and N. J. Van de Braak (eds.). Greenhouse climate control: an integrated approach. Wageningen Press, Wageningen, The Netherlands.

Glenn, E.P. 1984. Seasonal effects of radiation and temperature on growth of greenhouse lettuce in a high insolation desert environment. Scientia Hort. 22:9-21.

Hall, B.J. and S.T. Besemer. 1972. Agricultural plastics in California. HortScience 7(4):373-378.

Hancock, J. and D. Simpson. 1995. Methods of extending the strawberry season in Europe. HortTechnology 5(4):286-291.

Harper, J. 2003. Economics of high tunnel production, p. 140-143. In: W. Lamont, M. Orzolek, and L. White (eds.) High tunnel production manual. Center for Plasticulture, Department of Horticulture, College of Agriculture, Pennsylvania State University.

Healy, W., J. Hanson, and S. Gill. 1991. Starting in the greenhouse business. Cooperative Extension Fact sheet 593. University of Maryland. 19 Nov. 2006. <http://pubs.agnr.umd.edu/PDFs/FS593.pdf>.

Herner, R.C. 1986. Germination under cold soil conditions. HortScience 21(5):1118-1122.

Hicklenton, P. R. and M.S. Wolynetz. 1987. Influence of light- and dark-period air temperatures and root temperature on growth of lettuce in nutrient flow systems. J. Amer. Soc. Hort. Sci. 112(6):932-935.

Hochmuth, G.J., S.J. Locascio, S.R. Kostewicz, and F.G. Martin. 1993. Irrigation method and rowcover use for strawberry freeze protection. J. Amer. Soc. Hort. Sci. 118(5):575-579.

Hodges, L. and J.R. Brandle. 1996. Windbreaks: an important component in a plasticulture system. HortTechnology 6(3):177-181.

Hodges, L. M.N. Suratman, J.R. Brandle, and K.G. Hubbard. 2004. Growth and yield of snap beans as affected by wind protection and microclimate changes due to shelterbelts and planting dates. HortScience 39(5):966-1004.

Horne, J.E. and M. McDermott. 2001. The next green revolution: Essential steps to a healthy, sustainable agriculture. The Haworth Press.

Hume, D.J. and A. K.H. Jackson. 1981. Pod formation in soybeans at low temperatures. Crop Sci. 21:933-937.

Inoue, Y. and Y. Suzuki. 1959. Studies on the reproductive physiology of common beans *Phaseolus vulgaris.* VII. The effects of temperature on functioning of pollen and pistil. J. Hort. Assoc. Japan 28:19.

Jackson, L., K. Mayberry, F. Laemmlen, S. Koike, K. Schulbach, and W. Chaney. 1996. Leaf lettuce production in California. Division of Agriculture and Natural Resources Publication 7216. University of California Davis. 11 July 2006. <http://anrcatalog.ucdavis.edu/pdf/7216.pdf>.

Jahns, T.R. 2005. Alaska potato profile. University of Alaska Fairbanks; College of Rural Alaska; Cooperative Extension Service. 10 Oct. 2005. <http://www.uaf.edu/ces>.

Jenni. S., J.F. Dubuc, and K.A. Stewart. 2003. Plastic mulches and row covers for early and midseason crisphead lettuce produced on organic soils. Can. J. Plant Sci. 83:921-929.

Jones, L.H. 1971. Adaptive responses to temperature in dwarf French beans, *Phaseolus vulgaris* L. Annals of Botany 35:581-596.

Kemp, G.A. 1978. Growth of primary leaves of beans (*Phaseolus vulgaris* L.) under suboptimal temperatures. Can. J. Plant Sci. 58:169-174.

Kigel, J., I. Konsens, and M. Ofir. 1991. Branching, flowering and pod-set patterns in snap-bean (*Phaseolus vulgaris* L.) as affected by temperature. Can. J. Plant Sci. 71:1233-1242.

Kimball, M.H., W.L. Sims, and J.E. Welch, 1967. Plant climate analysis for lettuce. California Agr. 21(4):2-4.

King, C.A. and L.R. Oliver. 1994. A model for predicting large crabgrass (*Digitaria sanguinalis*) emergence as influenced by temperature and water potential. Weed Science 42:561-567.

Kitaya, Y., G. Niu, T. Kozai, and M. Ohashi. 1998. Photosynthetic photon flux, photoperiod, and CO_2 concentration affect growth and morphology of lettuce plug transplants. HortScience 33(6):988-991.

Klapwijk, D. 1979. Seasonal effects on the cropping cycle of lettuce in glasshouses during the winter. Scientia Hort. 11:371-377.

Kurtz, E.A. 2001. Crop profile of leaf lettuce in California. California lettuce research board, Salinas, Calif. 11 July 2006. <http://www.ipmcenters.org/cropprofiles/docs/calettuce-leaf.html>.

Laing, D.R., P.G. Jones, and J.H.C. Davis. 1984. Common bean (*Phaseolus vulgaris* L.), p. 305-351. In: P.R. Goldsworthy and N.M. Fisher (eds.). The physiology of tropical field crops. John Wiley and Sons Ltd.

Lamont, W.J., M.R. McGann, M.D. Orzolek, N. Mbugua, B. Dye, and D. Reese. 2002a. Design and construction of the Penn State high tunnel. HortTechnology 12(3):447-453.

Lamont, W.J., M.D. Orzolek, J. Holcomb, R.M. Crassweller, K. Demchak, E. Burkhart, L. White, and B. Dye. 2002b. Penn State high tunnel extension program. HortTechnology 12(4):732-735.

Lamont, W.J., M.D. Orzolek, E.J. Holcomb, K. Demchak, E. Burkhart, L. White, and B. Dye. 2003. Production system for horticultural crops grown in the Penn State high tunnel. HortTechnology 13(2):358-362.

Lorenz, H.P. and H.J. Wiebe. 1980. Effect of temperature on photosynthesis of lettuce adapted to different light and temperature conditions. Scientia Hort. 13:115-123.

Matheke, G.E.M., P.S. Holloway, and J.T. Hanscom. 2006. Cultivar trials on field-grown tomatoes., Alaska Agricultural and Forestry Experiment Station, Research Progress Report, No. 45.

Mattei, F., L. A. Sebastiani, and D. Gibbon. 1973. The effect of radiant energy on growth of *Lactuca sativa*. J. Hort. Sci. 48:311-313.

Monterosso, V.A. and H.C. Wien. 1988. Effect of high temperature on pod set of *Phaseolus vulgaris* L. Annual Report of the Bean Improvement Cooperative 31:160.

Nothmann, J. 1977a. Effects of soil temperature on head development of cos lettuce. Scientia Hort. 7:97-105.

Nothmann, J. 1977b. Morphogenetic effects of seasonal conditions on head development of cos lettuce (*Lactuca sativa* cv. Romana) growing in a subtropical climate. J. Hort. Sci. 52:155-162.

Pearson, S., T.R. Wheeler, P. Hadley and A.E. Wheldon. 1997. A validated model to predict the effects of environment on the growth of lettuce (*Lactuca sativa* L.): Implications for climate change. J. Hort. Sci. 27(4):503-517.

Penavaldivia, C.B., L.D. Lagunes, and H.R. Perales. 1994. Chilling effects on leaf photosynthesis and seed yields of *Phaseolus vulgaris*. Can. J. Bot. 72(10):1403-1411.

Purser, J. and M. Comeau. 1989. The effect of raised beds, plastic mulches and row covers on soil temperatures. 1989 Demonstration and Research Report, Cooperative Extension Service, University of Alaska Fairbanks.

Purser, J. and M. Comeau. 1990. The effect of raised beds, plastic mulches and row covers on soil temperatures. 1990 Demonstration and Research Report. Cooperative Extension Service, University of Alaska Fairbanks.

Purser, J. 1996. Plastic mulch and row covers for vegetable production in Alaska. Cooperative Extension Service, FGV-00647, University of Alaska Fairbanks.

Rainey, K.M. and P. D. Griffiths. 2005. Inheritance of heat tolerance during reproductive development in snap bean (*Phaseolus vulgaris* L.). J. Amer. Soc. Hort. Sci. 130(5):700-706.

Ross, N.J., M.D. Anderson, J.P. Goldberg, R. Houser, and B.L. Rogers. 1999. Trying and buying locally grown produce at the workplace: results of a marketing intervention. Amer. J. Alternative Agr. 14(4):171-179.

Safley, C.D., E.B. Poling, M.K. Wholgenant, O. Sydorovych, and R.F. Williams. 2004. Producing and marketing strawberries for direct market operations. HortTechnology 14(1):124-135.

Sciabarrasi, M. R. and O. S. Wells. 1999. Economic analysis of high tunnel tomato production. University New Hampshire, Coop. Ext. Fact Sheet. 22 Oct. 2006. <http://www.plasticulture.org/history_season_extension.htm>.

U.S. Dept. of Agriculture/National Agricultural Statistics Service. 2004. Vegetables Final Estimates 1998 to 2003. Statistical Bulletin Number 987. 2 Feb. 2006. <http://usda.mannlibb.cornell.edu/usda/nass/SB987.sb987.pdf>.

Wall, J., W.J. Lamont, and M.D. Orzoleck. 2000. Low-technology plastic greenhouses called high tunnels could help farmers extend growing season for many crops. College of Agricultural Science News Release Archive. 5 Oct. 2005. <http://www.aginfo.psu.edu/News/october00/tunnel.html>.

Waterer, D. 2003. Yields and economics of high tunnels for production of warm-season vegetable crops. HortTechnology 13(2):339-343.

Weaver, M.L., H. Timm, M.J. Silbernagel, and D.W. Burke. 1985. Pollen staining and high-temperature tolerance of bean. J. Amer. Soc. Hort. Sci. 110(6):797-799.

Wells, O.S. 1991. Guidelines for using high tunnels for tomato production. Univ. of New Hampshire Coop. Ext. Publ.

Wells, O.S. 2004. Season extension technology. American Society of Plasticulture, University of New Hampshire. 22 October 2006. <http://www.plasticulture.org/history_season_extension.htm>.

Wells, O.S. and J.B. Loy. 1985. Intensive vegetable production with row covers. HortScience 20(5):822-826.

Wells, O.S. and J.B. Loy. 1993. Rowcovers and high tunnels enhance crop production in the Northeastern United States. HortTechnology 3(1):92-95.

White, L. and M. Orzolek. 2003. A short history of protected horticulture: world and regional perspectives, p 6-9. In: W. Lamont, M. Orzolek, and L. White (eds.). 2003 High tunnel production manual. High tunnel production manual. Center for Plasticulture, Department of Horticulture, College of Agriculture, Pennsylvania State University.

Wien, H.C. 1997. Lettuce, p. 479-510. In: H.C. Wien (ed.). Vegetable crop physiology. CAB International.

Wittwer, S.H. and N. Castilla. 1995. Protected cultivation of horticultural crops worldwide. HortTechnology 5(1):6-23.

Wurr, D.C.E., J.R. Fellows, and G.E.L. Morris. 1981. Studies of the hearting of butterhead lettuce: temperature effects. J. Hort. Sci. 56:211-218.

Zhao, X., Carey, E.E., and Hall, M. 2003. Influence of protected environment and fertilizer source on growth and quality of lettuce and leafy greens during summer production in Kansas. Hortscience 38(5):749 (abstr.).

Zheni, M.S., F.S. Saad, D.G. Morgan. 1970. Photoperiod and flower bud development in *Phaseolus vulgaris*. Nature 227:628-629.

Chapter 2 Northern Field Production of Leaf and Romaine Lettuce using a High Tunnel[1]

Summary

A high tunnel environment was evaluated for production of leaf ('Two Star') and romaine ('Parris Island Cos') lettuce (*Lactuca sativa*) in a northern location (lat. 64°49'N). Ten plantings were made 1 week apart from May to August. In late May, mean air temperature was only 0.5 °C higher in the tunnel compared with the field, while in September temperature gains were 2.5 °C. 'Two Star' planted on 3 Aug. and harvested on 16 Sept. produced higher yield ($P < 0.001$) in the tunnel. Head weight was 195 ± 12 g in the tunnel and 99 ± 8 g in the field. For the 13 July planted 'Two Star' lettuce, the field produced significantly ($P < 0.001$) more at 202 ± 21 g/head than the 135 ± 29 g/head in the tunnel. The three consecutive field plantings of 1, 8 and 15 June resulted in higher 'Parris Island Cos' yields than corresponding plantings in the high tunnel. Head weights for harvests on 11, 18 and 25 July were 457 ± 60, 476 ± 65 and 478 ± 25 g under field conditions and 354 ± 46, 331 ± 52 and 312 ± 14 g in the high tunnel. 'Two Star' was observed less prone to bolting than 'Parris Island Cos'. Although a high tunnel did not generally support increased productivity in this study, the added protection resulted in high quality lettuce with limited necessary preparation and marketing loss in comparison to the field grown lettuce.

[1] Modified from published paper: Rader, H.B. and M.G. Karlsson. 2006. Northern Field Production of Leaf and Romaine Lettuce using a High Tunnel. HortTechnology 16(4):649-654.

Introduction

High tunnels are temporary field greenhouses that use solar heat to more rapidly increase air and soil temperatures than an open field (Lamont et al., 2003; Wells and Loy, 1993). These structures are manually ventilated and usually irrigated with drip tape, emitters, or soaker hoses. In general, high tunnels improve yield and crop quality through improved temperatures, lower disease and pest incidence (Waterer, 2003), and protection from rain, wind, and hail (Hodges and Brandle, 1996). For instance, high tunnels used for late winter strawberry production in Kansas improved earliness, yield, fruit quality and protected the plants from low winter temperatures (Kadir et al., 2006). Although high tunnel field production is used less often in North America compared with Europe, a range of crops are now successfully produced in various regions of the U.S. and Canada. Reasons for lower use in the U.S. could be due to lower transportation costs, cheaper food, highly centralized marketing systems, and consumer reluctance to pay for high quality, fresh, local produce (Hancock and Simpson, 1995). In areas with field seasons of moderate temperatures and limited duration, high tunnels may serve well to improve and extend crop productivity over the season.

Cos or romaine lettuce has long, narrow leaves that form oval shaped heads (Ryder, 1979) while leaf lettuce is characterized by soft open heads that are more easily damaged during shipment. California produces about 81% of U.S. leaf lettuce, the majority of which is romaine and a smaller percentage, green leaf lettuce (Kurtz, 2001). Generally, lettuce is considered a cool season crop with optimum production temperatures of 23 °C during the day and 7 °C at night (Jackson et al., 1996). Lower than optimal temperatures slow growth and temperatures beyond optimal often result in bolting, bitterness, tipburn, and poor heading. Higher than 32 °C may also result in thermodormancy.

Modern cultivars of leaf lettuce have been developed to tolerate warmer growing regions and conditions such as greenhouses (Bierhuizen et al., 1973; Wien, 1997). For lettuce to properly form heads, individual leaves need to be sufficiently large, petioles short, rate of stem elongation slow and the production of leaves adequately fast (Wien, 1997). Bolting, the failure to properly form a head due to excessively rapid stem elongation or leaf twisting (Nothmann, 1977a), may be especially problematic under combinations of elevated temperatures in high tunnels and the naturally extended daylengths of high latitude locations.

Temperature is the most important environmental factor for lettuce growth prior to complete soil coverage (Bierhuizen et al., 1973). Canopy extension was faster under elevated temperatures which led to increased light interception (Challa, 1990; Pearson et al., 1997). Even small temperature enhancements in a high tunnel environment may therefore significantly improve crop productivity. Though faster maturity and growth can be expected under slightly warmer conditions (Boxall, 1971), excessively high temperatures may be counter productive. Soil temperatures near 36 °C led to poor heading, leaf twisting, reduced leaf size, decreased head weight, and poor shoot and root development (Nothmann, 1977b). Vegetative head disintegration, a reversal of the rosette stage, was noted with soil temperatures at 28 to 36 °C (Nothmann, 1977b).

Increasing temperatures, irradiance, and daylengths in the spring slowed growth of romaine lettuce but still resulted in consistent heading with minimal leaf twisting (Nothmann, 1977a) and low bolting tendency (Bierhuizen et al., 1973). High temperature and irradiance in the summer limited leaf folding and produced soft, open heads with frequent bolting (Glenn, 1984; Nothmann, 1997a). In the fall, growth was initially rapid but decreased as temperature, irradiance, and daylength decreased (Nothmann, 1977a). In the cool temperatures of winter, growth was slow with late heading and limited bolting under the gradually increasing daylengths (Nothmann, 1977a).

In Kansas, lettuce grown in high tunnels bolted more quickly, tasted bitter, and had lower nitrate levels (Zhao et al., 2003). Wind speed was reduced although air temperature and relative humidity in the high tunnel were comparable to the open field. Several leaf lettuce cultivars including ‘Two Star’ were more heat and bolting sensitive when grown in the high tunnel (X. Zhao, personal communication). Overhead sprinkle irrigation and shading reduced bolting, but these practices may negate some of the benefits derived from high tunnel production.

Alaska field conditions differ significantly from those of major lettuce producing areas in the U.S. The limited growing season of high latitudes requires field establishment through sequential transplanting rather than direct seeding. Regions of California with extensive lettuce production have days of 17 to 28 °C and nights from 3 to 12 °C (Jackson et al., 1996). The average temperature during the field season of June, July and August in Fairbanks, Alaska (64°49'N, long. 147°52'W), has been recorded at 15.4 °C for 1996 through 2005 along with 10.1 °C minimum and 20.8 °C maximum averages (Alaska Climate Research Center, 2006). The longest day is 14 h and 41 min (U.S. Naval Observatory, 2006) in Salinas, California (lat. 36°41'N, long. 121°38'W) of the Monterey County lettuce producing area. In contrast, from mid May to end of July, civil twilight extends the day to 24 h (U.S. Naval Observatory, 2006) in interior Alaska (lat. 64°49'N).

High tunnels may be appropriate for improving and extending lettuce field production at high latitudes where frost, delayed snowmelt and other seasonable conditions may curtail an already short growing season. In Outlook and Saskatoon, Sask., Canada, the romaine lettuce cultivars Conquistador and Green Forest produced earlier and larger yields in a high tunnel environment (Waterer et al., 2005). The objective of our study was to evaluate yield and size differentials in a northern location for romaine and leaf lettuce planted sequentially throughout the season in a high tunnel and the field.

Materials and Methods

This study was conducted during the summer 2005 at the University of Alaska Fairbanks Experiment Farm (lat. 64°49'N, long. 147°52'W, elevation 144 m). From April to September, there is an average of 94 frost free days and 20.7 cm precipitation (Benz et al., 2005). The soil type at the growing site was a loamy, mixed, nonacid Pergelic Cryaquepts in the Tanana series (Furbush et al., 1980). Soils were analyzed in spring and autumn of 2005 at 0 to 15 cm depth (Appendix B).

A romaine type lettuce, ‘Parris Island Cos MI’, and a leaf lettuce, ‘Two Star MI’, were selected for the study. Pelleted seeds (Osborne International Seed Co., Mount Vernon, Wash.) were propagated in 200-cell plug flats using Premier Pro-Mix BX

(Premier Horticulture, Premier Brands, Inc., Red Hill, Pa.) for 4 weeks prior to transplant to the field. A ClearSpan, two bay high tunnel (ClearSpan, Dyersville, Iowa) with the dimensions of 15.8 m wide × 3.7 m high × 14.6 m long and covered with a single layer of 6-mil polyethylene plastic (Tyco Tufflite IV UV blocked, Tyco Plastics and Adhesives Division of Tyco, Inc., Monroe, La.) was used. A drip-tape irrigation system (T-tape; T-systems International, San Diego) with emitters spaced 20 cm apart with a flow rate of 250 $L \cdot h^{-1}$ per 100 m was used. The pH of the irrigation water was 7.4 and electric conductivity was 0.62 mmho/cm. Each plot was fertilized prior to planting at a rate of 20N-4.4P-8.3K using 540 $kg \cdot ha^{-1}$ (urea, triple phosphate, and potassium sulfate) based on recommendations for Oregon grown lettuce (Hemphill, 2004). Temperatures were recorded at 10 min intervals 15 cm below and 1 m above ground inside and outside the high tunnel using a Watchdog Data Logger temperature sensor, 400/200 Series, (Spectrum Technologies, Inc, Plainfield, Ill.). Temperatures for each calendar day were averaged and reported as monthly averages (Table 2.1). Side and end walls were manually opened and closed to provide ventilation during warm days.

A randomized complete block design was used. The main plot factor was environment (high tunnel or open field) and subplot factors were planting date and cultivar. Eighteen, uniform lettuce transplants were manually transplanted to 60 x 120-cm plots (0.72 m^2) approximately 25 cm apart in a 6 x 3 grid. Ten planting dates were incrementally spaced 1 week apart from 25 May to 10 Aug. (Table 2.2). The first lettuce was harvested on 4 July and the final harvest was 28 Sept. The earliest planting (18 May) was destroyed by high winds along with a single bay high tunnel. 'Two Star' planted on 1, 8, 15 and 22 June was rendered damaged beyond marketability quality by rodents. However, the final five plantings (13, 20 and 27 July, 3 and 10 Aug.) of 'Two Star', achieved maturity.

Periodic height measurements were made of five randomly selected plants from the 25 May, 15 June, 13 and 27 July, and 10 Aug. plantings. Entire plots were harvested approximately 6 weeks after planting when more than 50% of the plants had developed firm mature heads or were bolting in either location. Head weight and height were recorded and position in the plot noted. Several leaves of variable age were selected from four randomly chosen heads in the 21 June and 5 July plantings for soluble solid concentration (SSC) using a Digital Pocket Refractometer (Spectrum Technologies, Inc.). Four heads were also oven dried at 68 °C and weighed after 3 d. PROC GLM (SAS Institute Inc., Cary, N.C.) repeated measures analysis was used for growth rates using log transformed height while ANOVA was used for yield variables.

Results and Discussion

Air and soil temperature differentials between the tunnel and the field varied widely throughout the season (Fig. 2.1). With the ends of the tunnel left completely open in June, air averaged 1.2 °C and soil 0.2 °C higher than the field. In contrast, even late in the season, maximum daily temperature would increase rapidly in a closed tunnel under sunny conditions. Attention to ventilation practices was therefore essential as air averaged 2.5 °C and soil 2.6 °C higher than the field in an unventilated tunnel on 25 Sept.

The high tunnel offered some protection, when completely closed, during the first severe frost of 2 Sept. (Fig. 2.2) as reflected in an average 5.8 °C higher air and 3.5 °C higher soil temperature. The soil remained above freezing while air dropped to -1.7 °C in the tunnel and -4.6 °C in the field. Still, 'Parris Island Cos' and 'Two Star' were not damaged by frost in the high tunnel or in the field on 2 Sept.

Planting date affected yield and other measured variables for both cultivars (Table 1. 3). Although overall yield did not differ in the two environments for 'Two Star', there were significant interactions between environment and time of planting. The first planting on 25 May produced a larger yield than subsequent plantings with average head weight of 374 ± 36 g in the field and 421 ± 12 g in the tunnel (Fig. 2.3).

Growth and development of 'Two Star' planted on 13 July and 3 Aug. varied between environments. For 'Two Star' planted on 13 July, the field produced more ($P < 0.001$) at 202 ± 21 g/head than the 135 ± 29 g/head in the tunnel. Head weight averaged 195 ± 12 g in the tunnel and 99 ± 8 g in the field for the 3 Aug. planting.

The rate of height increase was only different ($P < 0.01$) for the 13 July 'Two Star' planting (data not shown). The daily elongation rate in the field was 5.5% and 3.7% in the tunnel. Percent dry mass was greater ($P < 0.05$) for lettuce growing in the field at 8.5% compared to 5.7% in the tunnel (data not shown). Sugar analysis for the 20 July planting suggested 5.3% SSC for tunnel grown and 6.5% for field grown lettuce (data not shown).

Environment significantly affected yield of 'Parris Island Cos' (Table 2.3) for three consecutive plantings in June (Fig. 2.3). Head weight for the 1 June planting was

457 ± 60 g in the field and 354 ± 46 g in the tunnel ($P < 0.05$). Similarly, the field produced larger heads (476 ± 65 g) than the tunnel (331 ± 52 g) for the 8 June planting. The 15 June planting had similar results at 478 ± 25 g/head and slightly smaller lettuce (312 ± 14 g) in the tunnel.

Growth of 'Parris Island Cos' based on height was faster in the tunnel for crops planted on 13 July ($P < 0.05$) and 10 Aug. ($P < 0.001$) (data not shown). Similar to 'Two Star', the dry weight proportion was higher in the open field ($P < 0.01$) at 6.3% than the 5.2% recorded in the tunnel for the 20 July and 3 Aug. plantings (data not shown). On the other hand, 'Parris Island Cos' had higher SSC values in the tunnel (5.4%) than the field (4.8%, data not shown).

The 1:1 pH level in spring 2005 averaged 6.26 and in autumn 2005 was 6.71 in the field compared with 7.10 in the tunnel. Available NO^-_3-N was 12 ppm in the field and 15 ppm in the high tunnel. Potassium (K) levels were lower in the tunnel compared with the field in autumn 2005 after only one season of production at 0.66 $meq \cdot 100\ g^{-1}$ in the open field and 0.18 $meq \cdot 100\ g^{-1}$ in the high tunnel. This is an important difference as less than 0.4 $meq \cdot 100\ g^{-1}$ soil is considered low while 0.6 to 2.0 $meq \cdot 100\ g^{-1}$ soil is considered high (Marx et al., 1999). Pre-season soil tests showed phosphorus levels of 188 ppm in the field and 198 ppm in the tunnel using the Mehlich 3-P soil test. When soils were tested in Autumn 2005, P was 220 ppm in the field and 174 ppm in the high tunnel. For vegetable production in the Tanana Valley, 115 ppm is considered a medium level of phosphorus, 170 is high, and 225 is very high (Michaelson and Ping, 1989). Sodium (Na) levels were 0.08 $meq \cdot 100\ g^{-1}$ higher in the high tunnel compared with the open field at

0.27 meq·100 g^{-1} in the field and 0.35 100 g^{-1} in the tunnel. Soluble salt (Electric Conductivity: EC) levels were 0.50 mmhos in the field and 0.62 mmhos in the tunnel which are both considered low values (Marx et al., 1999).

In general, lettuce planted prior to July produced higher yields. The lower productivity for lettuce planted mid-season may be due to higher than optimal temperatures during planting and establishment. However, poor transplant quality may also have contributed to the overall reduced growth. All lettuce seedlings were grown for 4 weeks in a greenhouse under natural irradiance and long days prior to field planting. Although attempts were made to maintain uniform propagation conditions, greenhouse temperature increased with the outside environment and up to 21 h 49 min between sunrise and sunset on 21 June (U.S. Naval Observatory, 2006). High irradiance, elevated temperatures and extended daylengths have previously been found to predispose lettuce transplants to bolting after planting (Dennis and Dullforce, 1974; Klapwijk, 1979). Direct seeding should be evaluated as an alternative to transplanting during the warmest period of the season. In addition to potential productivity improvements, direct seeding eliminates the need for an automated greenhouse and reduces labor for producing and planting lettuce transplants.

Growth rate based on height was not a useful indicator of yield potential for either 'Two Star' or 'Parris Island Cos'. The 13 July and 10 Aug. plantings of 'Parris Island Cos' increased faster in the tunnel probably due to excessive stem elongation rather than leaf expansion since yield differences were non-significant. No difference in elongation rate was observed between locations for 'Two Star' planted 3 Aug. although the tunnel harvest was larger. On the other hand, a more rapid height increase in field grown ‘Two Star’ planted 13 July did result in higher yield. Field grown lettuce also had higher dry weight proportion in this study. A higher SSC suggested ‘Two Star’ lettuce grown in open fields to be more palatable. Although ‘Parris Island Cos’ proportionally also had more dry weight, SSC did not increase in the field. Further studies are necessary to determine potential variations in dry weight, nutritional and taste characteristics between field and high tunnel grown lettuce.

Similar to ‘Two Star’, the productivity of ‘Parris Island Cos’ decreased as the season progressed through September (Fig. 2.3) in both environments. Additional time was required for the 10 Aug. planted lettuce to mature and harvest was delayed more than a week compared to most other plantings (Table 2.2). Decreasing air and soil temperatures are expected to slow growth, although other factors may influence late season lettuce production. Lettuce harvested on 16 and 28 Sept. was planted when temperatures were high on 3 and 10 Aug. The initial establishment and development at high temperatures may have affected the continued growth resulting in slower maturation.

Selecting head lettuce with sufficient resistance to bolting may be a challenge for extended days and elevated temperatures experienced during mid-summer in the far north. Careful evaluation is essential as the tendency to bolt has been observed to vary among cultivars and types of lettuce. For instance, the leaf lettuce ‘Salad Bowl’ was reported bolt resistant in local field trials while ‘Parris Island Cos’ was noted for high yield and quality but also increased tendency to bolt (Hébert and Matheke, 2004).

Cultivars with the phenotypic variability to exploit improved growing conditions should be identified (Wells and Loy, 1985). Zhao et al. (2003) tested 30 lettuce cultivars in Kansas and found romaine, oak leaf and butterhead types to be less likely to bolt than leaf lettuce in high tunnel environments. In our trials, we found the opposite: 'Two Star' seemed less prone to bolt compared to 'Parris Island Cos' in the high tunnel which may have been due to naturally prolonged days compared with Kansas.

Profit margins are highest early and late in the season when overall supply is low. The 3 Aug. planting of 'Two Star' suggested high tunnels would improve yields later in the growing season, but the first planting of 25 May did not show any advantage of a high tunnel environment for yield and rate of growth (Fig. 2.3). The option of temporarily heating the high tunnel during forecasted, mild frosts would further improve end of season crop dependability.

The historical average July temperature for Fairbanks Experiment Farm is 16.1 °C (Benz et al., 2005). July 2005 was recorded at a 2 °C higher average of 18.1 °C (Table 2.1). A colder, less optimal season than 2005 may further favor a high tunnel environment over the field for lettuce productivity. Even if lettuce yields were not significantly greater, the added protection from precipitation, wind, and to some extent frost should also be valued. Lettuce harvested in the high tunnel was clean while field grown lettuce required labor intense washing especially following heavy precipitation, before marketing.

Higher value, specialty crops with marginal hardiness are more likely to benefit from a seasonal, high tunnel growing area and should be prioritized to offset the additional construction and management costs of the structure. High value salad crops such as baby salad or specialty greens may also be more sensible choices for mid-season high tunnel production than leaf or romaine lettuce.

Literature Cited

Alaska Climate Research Center. 2006. Monthly time series data, Fairbanks, AK. Geophysical Institute, University of Alaska, Fairbanks, Alaska. 19 July 2006. <http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Fairbanks.html>.

Benz, S., G. Lucero, and C. Messer. 2005. Alaska agricultural statistics 2005. U.S. Dept. Agr., Natl. Agr. Stat. Serv., Alaska Field Office, Palmer, Alaska. 11 July 2006. <http://www.nass.usda.gov/Statistics_by_State/Alaska/Publications/Annual_Statistical_Bulletin/annual2005.pdf>.

Bierhuizen, J.F., J.L. Ebbens, and N.C.A. Koomen. 1973. Effects of temperature and radiation on lettuce growing. Neth. J. Agr. Sci. 21:110-116.

Boxall, M.I. 1971. Some effects of soil warming on plant growth. Acta Hort. 22:57-65.
Challa, H. 1990. Crop growth models for greenhouse climate control, p. 125-145. In: R. Rabbinge, J. Goudriaan, H. Van Keulen, F.W.T. Penning de Vries and H.H. Van Laar (eds.). Theoretical production ecology: reflections and perspectives. Simulation Monographs 34. Wageningen Press, Wageningen, The Netherlands.

Dennis, D.J. and W.M. Dullforce. 1974. Analysis of the subsequent growth and development of winter glasshouse lettuce in response to short periods in growth chambers during propagation. Acta Hort. 39:197-218.

Furbush, C.E., B.E. Koepke, and D.B. Schoephorster. 1980. Soil survey of Totchaket area, Alaska. U.S. Dept. of Agr. Soil Conservation Service. U.S. Government Printing Office, Washington D.C. 11 July 2006. <http://soils.usda.gov/survey/online_surveys/alaska/totchaket/totchaket.pdf>.

Glenn, E.P. 1984. Seasonal effects of radiation and temperature on growth of greenhouse lettuce in a high insolation desert environment. Scientia Hort. 22:9-21.

Hancock, J. and D. Simpson. 1995. Methods of extending the strawberry season in Europe. HortTechnology 5:286-291.

Hébert, M. and G. Matheke. 2004. Vegetable and fruit varieties for interior Alaska. University of Alaska Fairbanks, Cooperative Extension Service Publication HGA-00030, Fairbanks, AK. 11 July 2006. <http://www.uaf.edu/ces/publications/freepubs/HGA-00030.pdf>.

Hemphill, D. 2004. Lettuce *Lactuca sativa*. Oregon State University Extension Service, Commercial vegetable production guides, Corvallis, Oregon. 11 July 2006. <http://oregonstate.edu/Dept/NWREC/lettuce.html>.

Hodges, L. and J.R. Brandle. 1996. Windbreaks: an important component in a plasticulture system. HortTechnology 6:177-181.

Jackson, L., K. Mayberry, F. Laemmlen, S. Koike, K. Schulbach, and W. Chaney. 1996. Leaf lettuce production in California. Division of Agriculture and Natural Resources Publication 7216. University of California Davis. 11 July 2006. <http://anrcatalog.ucdavis.edu/pdf/7216.pdf>.

Kadir, S., E. Carey., and S. Ennahli. 2006. Influence of high tunnel and field conditions on strawberry growth and development. HortScience 41:329-335.

Klapwijk, D. 1979. Seasonal effects on the cropping cycle of lettuce in glasshouses during the winter. Scientia Hort. 11:371-377.

Kurtz, E.A. 2001. Crop profile of leaf lettuce in California. California lettuce research board, Salinas, Calif. 11 July 2006. <http://www.ipmcenters.org/cropprofiles/docs/calettuce-leaf.html>.

Lamont, W.J., M.D. Orzolek, E.J. Holcomb, K. Demchak, E. Burkhart, L. White, and B. Dye. 2003. Production system for horticultural crops grown in the Penn State high tunnel. HortTechnology 13:358-362.

Marx, E.S., J. Hart, and R.G. Stevens. 1999. Soil test interpretation guide. Cooperative Extension Service, EC 1478, Oregon State University.

Michaelson, G.J. and C.L. Ping. 1989. Interpretation of the phosphorus soil test for Alaska agricultural soils. Agricultural and Forestry Experiment Station, School of Agriculture and Land Resources Management, Circular 66, University of Alaska Fairbanks.

Nothmann, J. 1977a. Morphogenetic effects of seasonal conditions on head development of cos lettuce (*Lactuca sativa* cv. Romana) growing in a subtropical climate. J. Hort. Sci. 52:155-162.

Nothmann, J. 1977b. Effects of soil temperature on head development of cos lettuce. Scientia Hort. 7:97-105.

Pearson, S., T.R. Wheeler, P. Hadley, and A.E. Wheldon. 1997. A validated model to predict the effects of environment on the growth of lettuce (*Lactuca sativa* L.): implications for climate change. J. Hort. Sci. 27(4):503-517.

Ryder, E.J. 1979. Leafy salad vegetables. Avi, Westport, Conn.

U.S. Naval Observatory. 2006. Sunrise/sunset Table 1. for one year. Astronomical Applications Department, Washington, D.C. 11 July 2006. <http://aa.usno.navy.mil/>.

Waterer, D. 2003. Yields and economics of high tunnels for production of warm-season vegetable crops. HortTechnology 13:339-343.

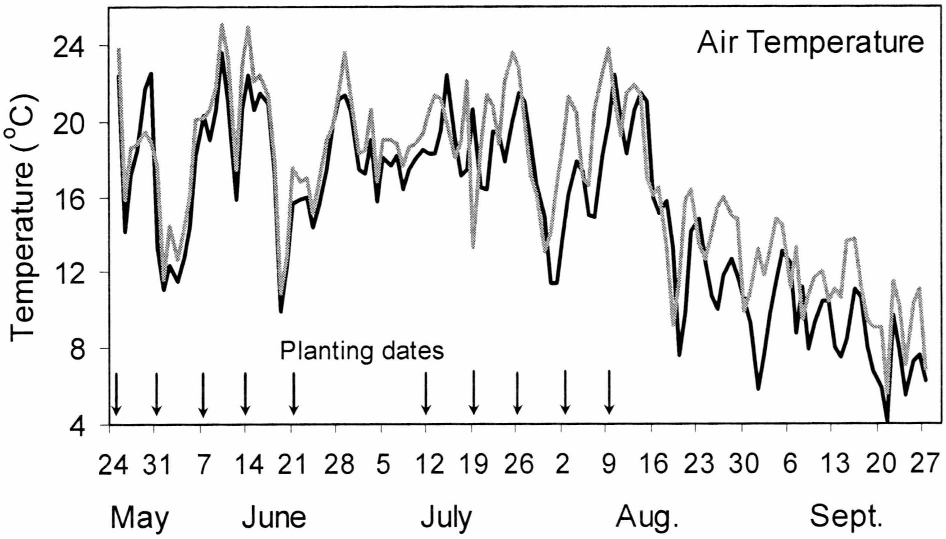
Waterer, D., J. Bantle, and W. Hrycan. 2005. Vegetable cultivars and cultural trials 2005. College of Agriculture, University of Saskatchewan, Sask., Canada. 11 July 2006. <http://www.usask.ca/agriculture/plantsci/vegetable/2005/2005veg/2005resources/2005VCCT.pdf>.

Wells, O.S. and J.B. Loy. 1985. Intensive vegetable production with row covers. HortScience 20:822-826.

Wells, O.S. and J.B. Loy. 1993. Rowcovers and high tunnels enhance crop production in the northeastern United States. HortTechnology 3:92-95.

Wien, H.C. 1997. Lettuce, p. 479-510. In: H.C. Wien (ed.). Vegetable crop physiology. CABI Publishing North America, Cambridge, Mass.

Zhao, X., E.E. Carey, and M. Hall. 2003. Influence of protected environment and fertilizer source on growth and quality of lettuce and leafy greens during summer production in Kansas. HortScience 38:749 (Abstr.).



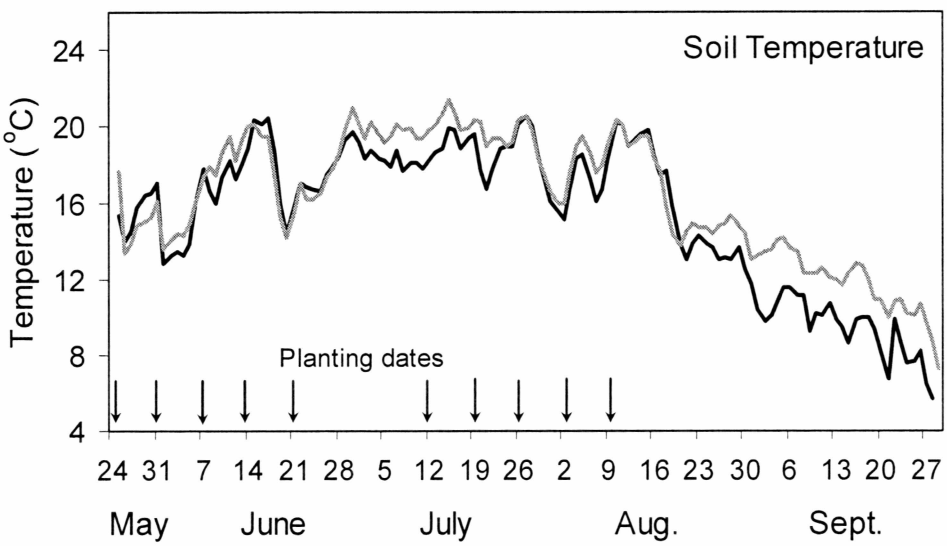


Fig. 2.1. Average daily air [1 m (3.3 ft.) above ground] and soil [15 cm (5.9 inches) depth] temperatures in a high tunnel (grey) and the open field (black) used to grow leaf lettuce 'Two Star' and romaine lettuce 'Parris Island Cos'. The arrows indicate the ten planting dates. 'Two Star' planted on 1, 8, 15 and 22 June did not mature due to severe rodent damage. (1.8 x °C) + 32 = °F.

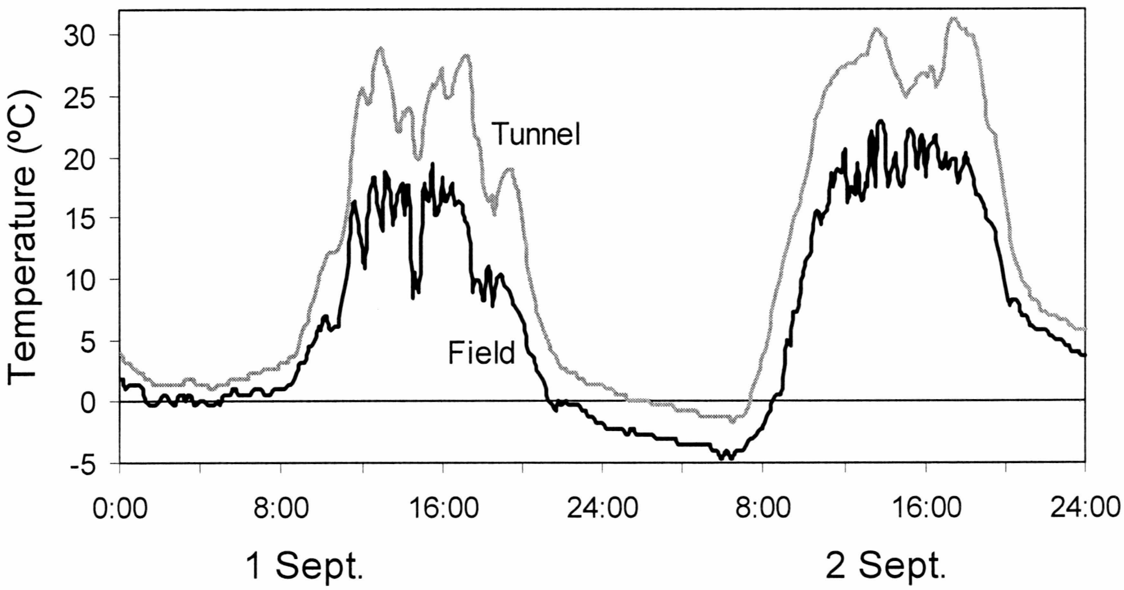


Fig. 2.2. Air temperature recorded every 10 min, 1 m (3.3 ft) above ground, in a high tunnel and open field used to grow leaf lettuce 'Two Star' and romaine lettuce 'Parris Island Cos'. The measurements were made on 1 and 2 Sept. 2005. (1.8 x °C) + 32 = °F.

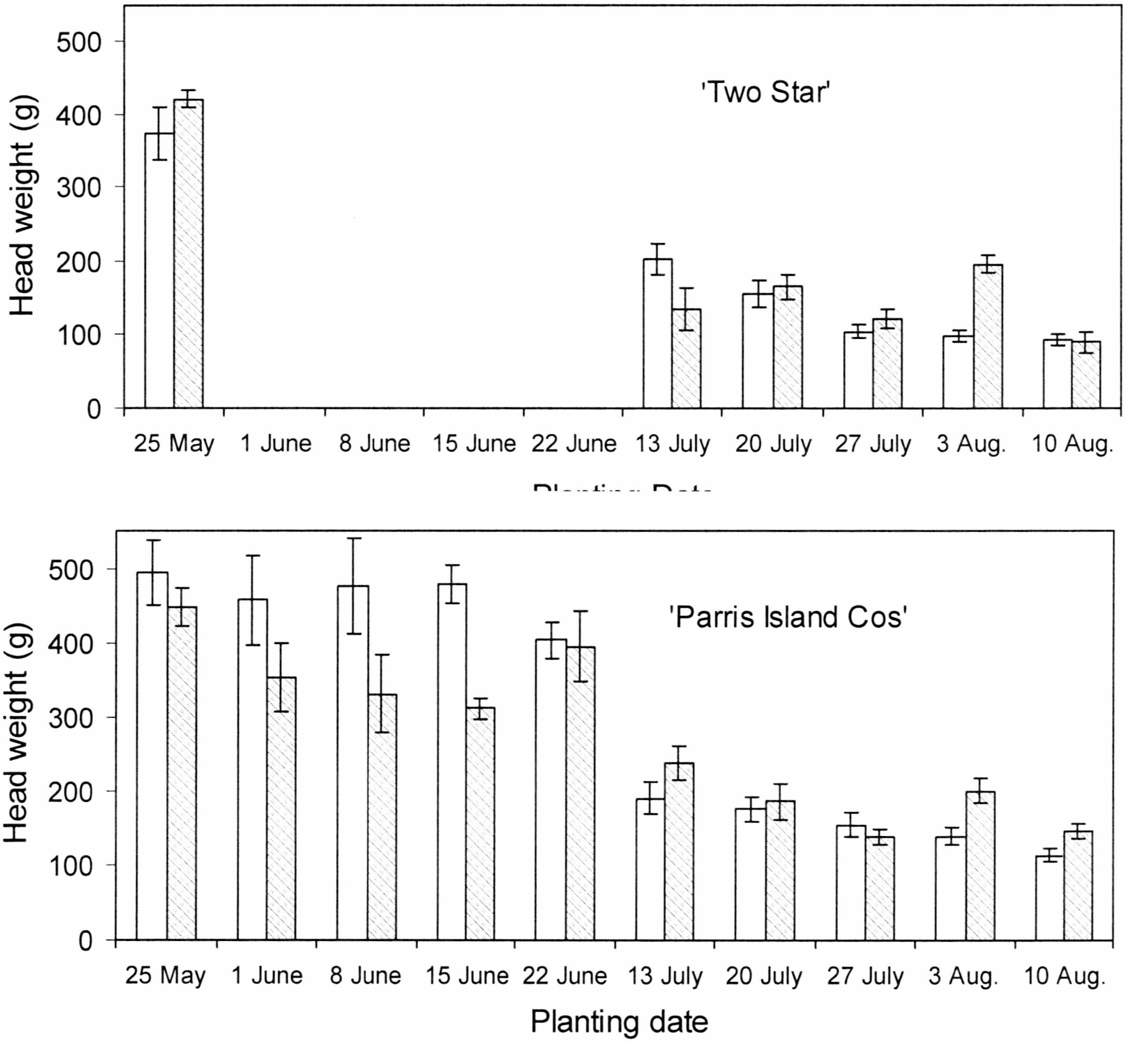


Fig. 2.3. Average lettuce head weight (g) with standard error bars, for each planting date of leaf lettuce 'Two Star' and romaine lettuce 'Parris Island Cos'. High tunnel lettuce is represented by cross hatched bars while field grown lettuce is represented by white bars. 1 g =0.0353 oz.

Table 2.1. Minimum, average and maximum temperatures in a high tunnel and the field used to grow leaf lettuce 'Two Star' and romaine lettuce 'Parris Island Cos'. Temperatures were recorded 1 m (3.3 ft) above ground and at 15 cm (5.9 inches) soil depth. Temperatures were recorded at 10 min intervals and averaged.

	Minimum		Average		Maximum	
Month	Tunnel	Field	Tunnel	Field	Tunnel	Field
			Air Temperature (°C)[z]			
Late May	8.3 ± 2.6	9.6 ± 2.9	19.0 ± 2.4	18.5 ± 3.8	31.6 ± 1.7	29.3 ± 4.0
June	9.1 ± 2.0	8.4 ± 2.1	18.7 ± 4.0	17.5 ± 3.8	30.8 ± 6.6	28.6 ± 6.2
July	9.9 ± 3.0	9.4 ± 2.9	19.3 ± 2.5	18.1 ± 2.1	31.6 ± 4.2	30.1 ± 3.5
August	7.5 ± 3.2	6.7 ± 3.6	16.9 ± 3.8	15.0 ± 4.0	29.5 ± 5.8	27.8 ± 6.6
September	4.0 ± 2.6	2.5 ± 3.0	10.6 ± 2.8	8.1 ± 3.0	22.7 ± 7.2	17.6 ± 6.7
May-Sept.	7.8 ± 2.7	7.3 ± 2.9	16.9 ± 3.1	15.4 ± 3.3	29.2 ± 5.1	26.7 ± 5.4
			Soil Temperature (°C)			
Late May	12.7 ± 0.9	13.4 ± 1.2	14.8 ± 0.9	15.7 ± 1.1	18.5 ± 4.1	19.0 ± 2.8
June	15.0 ± 1.8	14.7 ± 2.1	17.2 ± 2.0	17.0 ± 2.2	20.2 ± 3.4	20.2 ± 3.7
July	17.5 ± 1.4	16.5 ± 1.1	19.6 ± 0.9	18.6 ± 1.0	21.3 ± 1.2	20.8 ± 1.4
August	15.3 ± 1.8	14.4 ± 2.2	16.9 ± 2.1	16.1 ± 2.6	18.6 ± 2.3	18.0 ± 3.0
September	10.5 ± 2.3	7.9 ± 1.9	11.8 ± 1.7	9.2 ± 1.8	13.2 ± 1.9	10.7 ± 1.8
May-Sept.	14.2 ± 1.6	13.4 ± 1.7	16.1 ± 1.5	15.3 ± 1.7	18.4 ± 2.6	17.7 ± 2.6

[z](1.8 x °C) + 32 = °F.

Table 2.2. Average air and soil temperatures for each cropping period of leaf lettuce 'Two Star' and romaine lettuce 'Parris Island Cos' in a high tunnel and the field. Temperatures were recorded 1 m (3.3 ft) above ground and at 15 cm (5.9 inches) soil depth. Temperatures were recorded at 10 min intervals and averaged.

			Air (°C)[z]		Soil (°C)	
Planting	Harvest	Crop Days	Tunnel	Field	Tunnel	Field
25 May	4 July	40	18.8 ± 3.6	17.6 ± 3.6	17.0 ± 2.2	16.9 ± 2.0
1 June	11 July	40	18.7 ± 3.4	17.5 ± 3.3	17.9 ± 2.1	17.3 ± 2.0
8 June	18 July	40	19.6 ± 3.0	18.3 ± 2.7	18.8 ± 1.7	18.1 ± 1.3
15 June	25 July	40	19.1 ± 2.8	17.9 ± 2.5	18.9 ± 1.7	18.3 ± 1.3
22 June	1 Aug.	40	19.1 ± 2.7	17.9 ± 2.5	19.1 ± 1.4	18.3 ± 1.1
13 July	19 Aug.	37	19.3 ± 3.1	17.8 ± 2.8	18.9 ± 1.4	18.3 ± 1.4
20 July	30 Aug.	41	17.6 ± 3.6	15.9 ± 3.8	17.6 ± 2.1	16.9 ± 2.4
27 July	2 Sept.	37	16.7 ± 3.8	14.7 ± 4.3	16.9 ± 2.2	16.1 ± 2.9
3 Aug.	16 Sept.	44	15.2 ± 4.0	13.2 ± 4.4	15.5 ± 2.7	14.1 ± 3.6
10 Aug.	28 Sept.	49	13.2 ± 4.2	11.1 ± 4.7	14.0 ± 2.9	12.2 ± 3.9

[z](1.8 x °C) + 32 = °F.

Table 2.3. ANOVA with degrees of freedom (DF), F and P values for head weight and height of leaf lettuce 'Two Star' and romaine lettuce 'Parris Island Cos'. The lettuce was grown in a high tunnel or the field (environment). Six sequential plantings of 'Two Star' and 10 plantings of 'Parris Island Cos' reached maturity.

		Weight (g)[z]		Height (cm)[y]	
	DF	F-value	P-value	F-value	P-value
		'Two Star'			
Environment	1	2.43	0.1207	0.02	0.8959
Planting	5	73.61	< 0.0001	4.14	0.0013
Environment*planting	5	4.40	0.0008	1.74	0.1270
		'Parris Island Cos'			
Environment	1	5.15	0.0239	2.63	0.1055
Planting	9	32.85	< 0.0001	6.66	< 0.0001
Environment*planting	9	2.97	0.0021	3.41	0.0005

[z] 1 g = 28.3495 oz.

[y] 1 cm = 2.54 inches.

Chapter 3 High Tunnels Improved Snap Bean Production in Alaska[1]

Summary

Snap beans (*Phaseolus vulgaris* L.) were successionally planted in a high tunnel (temporary field greenhouse) at a high latitude location (lat. 64°49' N) throughout summers 2005 and 2006. Two cultivars with varying degrees of adaptation to northern climates were chosen for this study. 'Provider' (8.0 to 10.5 mm pods) is a proven performer at high latitudes, while 'Concesa' (<6.5 mm diameter pods) is more suited to southern climates. In 2005, plots were seeded from May to mid-July at bi-weekly intervals, while plots in 2006 were first seeded in late May, then subsequently reseeded in mid-June due to poor emergence rates. When the first fall frost killed the field grown snap beans, inside plants were protected from senescence both in 2005 without and with additional heat in 2006. Dates of last spring and first autumn frosts varied as much as one month between the two years. Although 'Provider' produced significantly more ($P <$ 0.001) overall (2.54 ± 1.27 kg·m^{-2}) than 'Concesa' (1.12 ± 0.81 kg·m^{-2}), 'Concesa' performed better in the high tunnel (1.72 ± 0.52 kg·m^{-2}) compared to field production (0.52 ± 0.54 kg·m^{-2}) ($P < 0.005$). 'Provider' produced more in the high tunnel in 2006 (2.40 ± 0.17 kg·m^{-2}) compared to the field (1.15 ± 0.08 kg·m^{-2}), but differences were not statistically significant when seasons were combined. The perceived benefits of high tunnel production included frost, wind, pest, and rain protection, improved yields, decreased weed emergence and moisture accumulation, as well as provided a pleasant working environment regardless of weather.

[1] Prepared for submission in HortTechnology, Rader, H.B. and M.G. Karlsson. 2006.

Introduction

Snap bean (*Phaseolus vulgaris* L.) is a warm season crop sensitive to adverse conditions. At all stages of growth, snap beans are prone to injury from cold (Dickson and Boettger, 1984), and wind (Finch, 1988; Hodges et al., 2004). Cultivars bred for high or low temperature tolerance exhibited decreased response to optimal temperatures (Dickson and Boettger, 1984; Rainey and Griffiths, 2005). Two cold tolerant accessions grown in S. Alberta had higher leaf area and dry matter in May compared with two commercially grown cultivars, but by mid-July the commercial varieties had overtaken the accessions (Freyman et al., 1979). Varieties with large seeds often emerge earlier at low temperatures (Kemp, 1978), but are often less palatable (Davis, 1997). For regions with short growing seasons such as Fairbanks, Alaska (lat. 64°49'N, long. 147°52'W), cold hardy cultivars or plasticulture techniques are usually required to produce mature snap beans.

Although some snap bean cultivars are cold tolerant, this does not imply tolerance to frost. First and last frost dates in Fairbanks can vary significantly from year to year and sometimes cause significant, economic hardship. For snap bean field production in Saskatchewan (52°07', 106°38'W), Balasubramanian et al. (2003) asserts, "The risk of economic losses due to a possible late spring frost injury must be weighed against the risk of economic losses caused by early fall frost." With high tunnels, the risk can be lowered significantly and yields improved markedly due to season extension as was shown in both summer 2005 and 2006. Growing Degree Days (GDD) can also be increased so that higher quality, but not necessarily cold tolerant cultivars could be produced.

High tunnels are simple structures constructed of metal bows and covered with one layer of 6-mil greenhouse-polyethylene plastic that warms the air and soil inexpensively (Wells, 2004). Endwalls are constructed in a variety of ways from unsupported plastic to wooden frames with a hinge that swing out for cultivation (Lamont et al., 2002). A defining characteristic of high tunnels is sufficient height to allow the use of tractors and other equipment, unlike hoop houses which are high enough to walk through, and unlike low tunnels or row covers which cover a single row of crops. Manual ventilation is often used in high tunnels to mitigate high air humidity and temperatures. Manual ventilation can be labor intense but is still more efficient than row covers or low tunnels. Drip irrigation is often used and temporary heating may be installed (Lamont et al., 2003; Wells and Loy, 1993; Wells, 2004).

Although the initial capital investment for high tunnels is low, they do require additional management compared with open field production. High value, warm season crops and cultivars are usually most profitable (Wall, 2000), although most crops benefit from a high tunnel environment via shelter from wind (Hodges and Brandle, 1996), rain, hail, disease (through reduced moisture), and other pests (Waterer, 2003, Lamont et al., 2003; Wells, 2004). High tunnels are especially cogent for crops which are harvested successively such as strawberries, snap beans, and bell peppers (personal observation). In spring or fall when forecasted frosts dictate covering crops with frost cloth or plastic coverings, the labor required for manually removing and replacing row covers is much more extensive compared with managing a high tunnel. Frost hardy crops that are harvested one time such as lettuce, onions, and potatoes do not seem to justify high tunnel space even if higher yields were achieved. On the other hand, a high value crop such as tomatoes yielded enough in one year to compensate for the additional costs of infrastructure associated with the high tunnel (Sciabarrasi and Wells, 1999; Waterer, 2003). If fuel prices continue to rise, there may be more incentive for plasticulture techniques, including high tunnels, to be employed for a wider range of crops (Hancock and Simpson, 1995).

High tunnels may be especially beneficial in improving proportion and rate of snap bean emergence by raising soil temperatures in the spring. The optimum temperature for snap bean emergence is 25 °C, while 18 to 29 °C is best for ensuing growth (Aguiar et al., 1998). Temperatures higher than 32 °C can cause blossom drop and ovule abortion. Dickson and Petzoldt (1987) found that soils of 10 °C or lower during imbibation and germination resulted in vigor reduction, and 15 to 16 °C in stunted growth or after an extended period, in no crop. Balasubramanian et al. (2003) said planting in Saskatchewan is postponed until late May when soil temperatures approach 20 °C to promote high germination rates and limit injury from cold.

'Provider' is widely grown in the Fairbanks area because of its early maturity and consistent high yields (Wagner et al., 1989). Consumers prefer snap beans with smaller diameter because of smoothness, flavor, and tenderness (Mullins and Straw, 2001), but they are often not the highest yielding or cold tolerant varieties. Varieties with extra-fine pods (< 6.5 mm diameter) produced 25% to 30% less than varieties with very fine (6.5 to 8.0 mm diameter) or fine (8.0 to 10.5 mm diameter) pods (Davis, 1997). Snap beans with larger seeds and cotyledons were more cold tolerant and produced more vigorous yields early on, but had lower consumptive quality (Austin and Maclean, 1972; Kemp, 1978). Finer snap beans often mature more slowly as well: ‘Maxibel’ and ‘Fandango’ are slender beans maturing in 60 and 62 d as opposed to ‘Provider’ and ‘Concesa’ which mature in 52 to 54 and 55 d, respectively (Osborne International Seed Company, 2006).

When fresh market supplies are low early in the spring and late in the fall, prices at the Tanana Valley Farmer’s Market are usually higher. In Fairbanks, growers charge as much as $4.50/lb. and as little as $1.50/lb., depending on snap bean supply (personal communication, G. Kerndt, P. Mayo). Higher quality cultivars that only produce satisfactorily in high tunnels may further increase profits.

With a short growing season in Fairbanks starting in late May and ending in September, temperatures average 15.4 °C with lows of 10.1 °C and highs of 20.8 °C (Alaska Climate Research Center, 2006a). We expected that increased air and soil temperatures in the high tunnel would result in higher snap bean yields, shorter maturity times, and a longer production season overall. During the shoulder seasons, snap bean production may be less risky and warrant a great investment in labor and space if grown in a high tunnel. High tunnel use in Alaska could extend the production season of traditional snap bean cultivars as well as improve productivity of higher quality cultivars.

Materials and Methods

This study was conducted during summers 2005 and 2006 at the University of Alaska Fairbanks Experiment Farm (lat. 64°49'N, long. 147°52'W, elevation 144 m). Fairbanks averages 115 frost free days from May to September (Benz et al., 2005), however the 2005 and 2006 growing seasons approached record late and early frosts

(Table 3.1). Precipitation averages 20.7 cm during the growing season. At the growing site, the soil type was a loamy, mixed, nonacid Pergelic Cryaquepts in the Tanana series (Furbush et al., 1980). Soils were analyzed in spring and autumn of 2005 and 2006 (Appendix B). All soil tests were done at a 0 to 15 cm depth.

Two snap bean cultivars, Concesa and Provider (Osborne International Seed Co., 2006), were used for this study. They were direct seeded after being inoculated with *Rhizobium* inoculum for four hours.

A ClearSpan, two bay high tunnel (ClearSpan, Dyersville, Iowa) with the dimensions of 15.8 m wide × 3.7 m high × 14.6 m long and covered with a single layer of 6-mil polyethylene plastic (Tyco Tufflite IV UV blocked, Tyco Plastics and Adhesives Division of Tyco, Inc., Monroe, La.) was used. Beds were made 60 cm wide, 20 cm high, 80 cm apart, with a bed shaper and mulch layer (Model 94, Mechanical Transplanter Company, Holland, MI), that simultaneously laid drip-tape (T-tape; T-systems International, San Diego) with emitters spaced 20 cm apart with a flow rate of 250 $L \cdot h^{-1}$ per 100 m. The pH of the irrigation water was 7.4 and electric conductivity was 0.62 mmho/cm. Each plot was fertilized prior to planting at a rate of 14N-6.3P-5.4K using 257 $kg \cdot ha^{-1}$ (urea, triple phosphate, and potassium sulfate) based on recommendations for snap bean production (Aguiar et al., 1998).

Temperatures were recorded every 10 to 30 min, 15 cm below and 1 m above ground inside and outside the high tunnel using a Watchdog Data Logger temperature sensor, 400/200 Series, (Spectrum Technologies, Inc, Plainfield, Ill.) from 25 May to 20 Sept. in all locations and in summer 2006, until 30 Sept. Mean temperature was calculated for each calendar day using Specware 7 Professional (Spectrum Technologies, Inc, Plainfield, Ill.) and reported as monthly means, average highs, and average lows (Table 3.2). Growing Degree Days (GDD) were calculated from tunnel and field air temperatures as follows: $\frac{1}{2}(T_{high} + T_{low}) - 10$ °C = GDD. If temperatures exceeded 30 °C, 30 was used for T_{high} while 10 was used for T_{low} if temperatures dropped below10 °C (Table 3.1). Chill hours were calculated for summer 2006 as the number of hours per calendar day where air temperatures were between 0 and 10 °C.

Relative humidity in the tunnel was measured with a ECH$_2$0 Logger, Em50 (Decagon Devices, Inc., Pullman, WA) and compared with local weather service humidity records (Alaska Climate Research Center, 2006a). Light measurements were made with a LI-190 Quantum sensor and recorded with a model LI-1400 data logger (LI-COR, Inc., Lincoln, Nebraska).

Side and end walls were manually opened and closed in the morning and at night, respectively, usually as temperatures reached 25 °C in the tunnel or to reduce excess moisture in the tunnel. In summer 2005, additional heat was not used in the high tunnel and additional frost protection was not used in the open field. However, in summer 2006, an additional heat source was used in the high tunnel at night, starting 24 Aug. set for 7.0 °C and Reemay frost cloth (Reemay Inc., Old Hickory, Tenn.) was used as a floating row cover for field plots beginning at the same time. The Reemay was a spun-bounded polyester with up to 80% of available light penetration and 1 to 2 °C of frost protection.

Thirty seeds were manually planted at 4 cm depth, 8 cm apart in two rows in a 60 x 120-cm plot. There were six bi-weekly plantings in 2005, of which three (25 May, 6

June, and 22 June) produced marketable pods. The first planting 18 May was destroyed by high winds along with the first high tunnel used for the study, while the 13 and 27 July plantings failed to mature due to frost. In 2006, plots were initially planted 26 May but due to an especially cold spring, plots were reseeded and transplanted 21 June. In 2006, each cultivar was planted in both bays of the tunnel and in the field in front of the tunnel for replication. Plots were hand-weeded and hand-watered if necessary. Ladybird beetles (*Hippodamia convergens*) were released as needed for aphid and whitefly mitigation.

Rate of emergence and flowering was recorded for all plots in 2005 and used to develop a phenological chart correlated with GDD for both cultivars (Fig. 3.1). After the onset of maturity, pods were generally harvested weekly. For each cultivar, length, weight, width, and gauge were measured on 12 individual beans, to obtain an average and range of bean sizes. As productivity declined, plants were harvested in 2005 to obtain fresh weight, dry weight, and length.

A completely randomized block design was used with location (high tunnel vs. open field) as main plot factors and cultivar as subplot factors. Cumulative yield (kg) and cumulative number of pods for each plot was used for analysis (Table 3.3). Planting dates were used as replicates in 2005, and in 2006 field and tunnel replications for the same planting date were used. Microsoft Excel Data Analysis Tool Pack was used to assess the effect of location and cultivar on yield. The paired t-Test was used with a two-tail P-value. The Bonferroni correction was used to determine significance with location and cultivar being the joint estimations.

Results and Discussion

Overall temperatures and frost dates were somewhat different for 2005 and 2006 growing seasons. June 2005 averaged 16.4 °C compared with a normal value of 15.1 °C and a June in 2006 of 14.5 °C (Alaska Climate Research Center, 2006a).Spring and fall frosts approached records in both summers (Table 3.1). The high tunnel protected snap beans from frost in both years with (2006) and without (2005) additional heat. Although the first frost on 2 Sept. 2005 minimally damaged high tunnel plants, they were protected from complete senescence, unlike snap beans in the open field which were completely desiccated (Fig. 3.2). On 2 Sept. 2005, the temperature averaged 5.8 °C and the soil 3.5 °C higher in the tunnel, while minimum air and soil temperatures recorded were -1.7 and 10.9 °C in the tunnel and -4.6 and 8.2 °C in the field (Fig. 3.3).

July precipitation in 2005 (8.74 cm) and 2006 (5.69 cm), also differed significantly from a normal value of 4.39 cm (Alaska Climate Research Center, 2006a). July 2006 recorded 18 d of light rain, 6 of rain, 3 of heavy rain, and 2 of thunderstorms when a normal July is hot with high fire danger.

Average relative humidity from mid-July to mid-Aug. 2006 was 64.2% in the tunnel and 71% for local climate records while the tunnel low averaged 33.2 % the high 91.2 % compared with climate records which averaged a low of 50% and a high of 92% (Alaska Climate Research Center, 2006a). Research on Penn State High Tunnels showed that in the summer, relative humidity averaged 80 % to 90 % from 9 PM to 6 AM compared with 30 % or lower during daylight hours (Burkhart and White, 2003). They also found that humidity was lower in the middle of the tunnel by about 4 % to 7% and could influence transpiration rates and disease mitigation. Compared with the tunnel at full sun (1000 to 1800 HR), average maximum light was 89.5% that of the field for measurements taken in August and September.

GDD varied with location, month and year (Table 3.4). GDD was highest for summer 2005 inside the high tunnel (1065.4) and lowest for summer 2006 in the high tunnel (887.6). Ventilation practices can change the high tunnel environment drastically. Wells (2004) recommends opening the sides each morning to decrease moisture and prevent high temperatures. In summer 2005 average air and soil temperatures were higher than the field. However, in 2006 when the summer was rainy and humid, the high tunnel averaged lower temperatures than the field, presumably due to opening sides and ends and converting the tunnel more into a shade cloth rather than a solar greenhouse. Low temperatures in the high tunnel were still higher than in the field because the tunnel was generally closed at night and heated late in the season. In contrast, even late in the season in 2005, maximum daily temperature increased rapidly in a closed tunnel under sunny conditions. Attention to ventilation practices was therefore essential as air averaged 2.5 °C and soil 2.6 °C higher than the field in an unventilated tunnel on 25 Aug. Chill hours for summer 2006 were 611.5 in the tunnel and 738.5 in the open field.

Spring soil temperatures were lower in 2006 than 2005 which presumably led to poor emergence rates and the need for reseeding (Table 3.2). In late May 2005, tunnel and field soil temperatures averaged 14.8 and 15.7 °C compared with 2006: 12.7 and 12.5 °C. June soil temperatures averaged more than 2 °C higher in 2005 compared with 2006.

As higher temperatures are more important for emergence than growth, an initially closed tunnel may be an important way to decrease time to maturity.

Soil fertility diverged after only two seasons of high tunnel production. The 1:1 pH level of autumn 2006 was 6.98 in the field and 7.20 in the high tunnel. Available NO^{-}_{3}-N averaged higher in the tunnel (33 ppm) compared with the field (12 ppm) for the final two soil tests. Available potassium (K) was lower in the tunnel compared with the field from autumn 2005 to autumn 2006. Average potassium was 0.73 meq·100 g^{-1} in the open field and 0.22 meq·100 g^{-1} in the high tunnel. This is an important difference as less than 0.4 meq·100 g^{-1} soil is considered low while 0.6 to 2.0 meq·100 g^{-1} soil is considered high (Marx et al., 1999). Pre-season soil tests showed phosphorus levels of 198 ppm in the field and 188 ppm in the tunnel using the Mehlich 3-P soil test while the final soil test in autumn 2006 indicated levels of 329 in the field and 300 in the tunnel. For vegetable production in the Tanana Valley, 225 is considered very high and additional P_2O_5 should not be applied (Michaelson and Ping, 1989). There were no noticeable differences in sodium (Na) levels between the high tunnel and field overall. Soluble salt (Electric Conductivity: EC) levels in the tunnel were 1.26 mmhos (medium) and 0.72 mmhos (low) in the field after the autumn 2006 test.

'Provider' emerged, flowered, and matured earlier than 'Concesa' (Figs. 3.1, 3.2). Emergence rates of 'Provider' were similar in both locations except for the 22 June 2005 planting which emerged faster in the tunnel. Fifty percent of 'Concesa' seeds germinated 6 and 8 d earlier in the tunnel for the 25 May and 6 June planting, respectively, and 8 d earlier in the field for the 22 June planting. In the tunnel in 2005, both cultivars flowered

2 to 7 d earlier which also led to earlier pod maturity. Regardless of location, ‘Provider’ produced more (2.54 ± 1.27 kg·m^{-2}) than ‘Concesa’ (1.12 ± 0.81 kg·m^{-2} ($P < 0.001$). Overall, differences in yield between location were not statistically significant, but in summer 2006 ‘Provider’ produced 2.40 ± 0.17 kg·m^{-2} in the tunnel compared with 1.15 ± 0.08 kg·m^{-2} in the field.

Overall, high tunnel production of ‘Concesa’ (1.72 ± 0.52 kg·m^{-2}) was more than double that of the field (0.52 ± 0.54 kg·m^{-2}) ($P < 0.005$). Maturation was also slightly earlier in the high tunnel and allowed production to continue after the first frost (Fig. 2). The 22 June 2005 planting produced mature beans in the tunnel, but failed to mature in the field. Overall, quantity of ‘Concesa’ beans harvested in the tunnel was significantly greater than in the open field ($P < 0.0005$).

‘Provider’ beans averaged 160 mm in length, 11 mm in diameter., and weighed 11 g. Individual beans could reach sizes of 190 mm long, 13 mm diam., and 15 g in weight, and were prone to overmature resulting in fibrous pods. ‘Provider’ could be hand-picked at a very fine sieve size, but machine harvested snap beans are usually picked once which prohibits multiple harvests. ‘Provider’ pods averaged 4.6% Brix and 7.63% dry weight with no significant difference between the tunnel or field locations. Above ground biomass did not differ between tunnel (6.70 kg) and the field (7.95 kg). Percent dry weight for individual plants averaged $22.4\% \pm 0.0649\%$.

‘Concesa’ beans were generally harvested at a gauge size of 3 which is 10 mm in diameter and classified as fine. Individual beans averaged 165 mm in length, 10 mm in diameter, and 8 g in weight. Beans could be picked at a smaller gauge size, but generally did not get reach sizes larger than 10 mm in diameter. 'Concesa' pods averaged 4.9% Brix and 8.18% dry weight with no significant difference between the tunnel and the field. Above ground plant biomass for mature plants was 7.62 kg in the tunnel and 8.00 kg in the field. Percent dry mass averaged 17.8% ± 2.13%.

Depending on sensitivity to cold, low soil temperatures may affect rate and proportion of snap bean germination (Herner, 1986). Although optimum germination has been reported at 25 °C (Aguiar et al., 1998), small seeded cultivars tolerate up to 28 °C (Laing et al., 1984) while large seeded cultivars still have good germination at 12 °C (Austin and Maclean, 1972). 'Provider' with a larger seed than 'Concesa' appeared to follow this trend. The radicles emerged at 10 to 12 °C in cold tolerant lines only while in standard cultivars the radicle emerged at soil temperatures of 8 °C but then either rotted or resulted in a weak plant (Dickson and Boettger, 1984). Seeds emerging after the temperature reached 20 °C had normal growth.

Mean soil temperature gains in the high tunnel were 0.9 °C in 2005 and 1.3 °C in 2006 (Table 3.2). When additional heat was used in Sept. 2006 the mean difference was 2.3 °C. If a heat source had been used in spring 2006, it may have elevated temperatures in the tunnel enough for adequate germination rates and eliminated the need for reseeding 21 June. Due to reseeding, snap beans lost more than 200 GDD in either location from 25 May to 21 June. 'Provider' averaged at least 500 GDD to achieve mature snap beans while 'Concesa' averaged at least 600 GDD until first harvest (Fig. 3.1). The high tunnel with or without additional heat could sufficiently improve GDDs for other high quality cultivars with less cold tolerance for successful production.

Management decisions regarding ventilation could also influence germination and growth rates. A high tunnel with crops of similar temperature optima could be kept at more optimal conditions. Waterer (2003) did not ventilate until tomatoes had flowered, and subsequently allowed the temperature to rise to 40°C before ventilation. Bell peppers were grown with the tomatoes with minimal heat stress. Less stringent ventilation practices led to a greater, average difference in GDD than experienced at our study sites. In Saskatchewan, GDD over 3 years averaged 1891 in the high tunnel and 1167 in the open field (Waterer, 2003).

Reliable snap bean production under unfavorable field conditions can be expected especially profitable. High tunnel use to lengthen and optimize seasonal growing conditions should be accompanied with cultivar selection for phenotypic plasticity to capitalize on improved environmental conditions. Snap beans are popular at local farmer's market and especially during low overall supply, can be priced accordingly. Opportunities to increase price for higher quality cultivars may also exist. Increased reliability, faster maturity, and higher yields suggest high tunnel snap bean production to be an appropriate choice for Fairbanks producers.

Literature Cited

Aguiar, J., F. Laemmlen, A. Baameur, and K. Mayberry. 1998. Snap bean production in California. Division of Agriculture and Natural Resources, Publication 7240. University of California Davis. 11 July 2006. <http://anrcatalog.ucdavis.edu/pdf/7240.pdf>.

Alaska Climate Research Center 2006a. Monthly time series data, Fairbanks, AK. Geophysical Institute, University of Alaska, Fairbanks, Alaska. 19 July 2006. <http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Fairbanks.html>.

Alaska Climate Research Center 2006b. Frost/freeze dates of occurrence and length of growing season, Fairbanks, AK. Geophysical Institute, University of Alaska, Fairbanks, Alaska. 28 Jan. 2006. <http://climate.gi.alaska.edu/Climate/Atlas/tables/Temperature/ff8.html>.

Austin, R.B. and M.S.M. Maclean. 1972. A method for screening *Phaseolus* genotypes for tolerance to low temperatures. J. Hort. Sci. 47:279-290.

Balasubramanian, P., A. Vandenberg, and P. Hucl. 2003. Planting date and suboptimal seedbed temperature effects on dry bean establishment, phenology and yield. Can. J. Plant Sci. 84:31-36.

Benz, S., G. Lucero, and C. Messer. 2005. Alaska agricultural statistics 2005. Palmer, Alaska Agr. Statistics Service, U.S. Dept. of Agr.

Burkhart, E.P. and L.D. White. 2003. The high tunnel cropping environment: understanding how things work, p. 45-56. In: W. Lamont, M. Orzolek, and L. White (eds.). High tunnel production manual. Center for Plasticulture, Department of Horticulture, College of Agriculture, Pennsylvania State University.

Davis, J.H.C. 1997. *Phaseolus* beans, 409-428. In: H.C. Wien (ed.). Vegetable crop physiology. CAB International.

Dickson, M.H. and M.A. Boettger. 1984. Emergence, growth, and blossoming of bean (*Phaseolus vulgaris*) at suboptimal temperatures. J. Amer. Soc. Hort. Sci. 109:257-260.

Dickson, M.H. and R. Petzoldt. 1987. Inheritance of low temperature tolerance in beans at several growth stages. HortScience 22(3):481-483.

Finch, S.J. 1988. Field windbreaks: Design criteria. Agr. Ecosystem and Environ. 22/23:215-228.

Freyman, S., G.A. Kemp, and D.B. Wilson. 1979. Growth of bean accessions at various temperatures. Can. J. Plant Sci. 59:81-85.

Furbush, C.E., B.E. Koepke, and D.B. Schoephorster. 1980. Soil survey of Totchaket area, Alaska. U.S. Dept. of Agr. Soil Conservation Service. U.S. Government Printing Office, Washington D.C. July 11 July 2006. <http://soils.usda.gov/survey/online_surveys/alaska/totchaket/totchaket.pdf>.

Hancock, J. and D. Simpson. 1995. Methods of extending the strawberry season in Europe. HortTechnology 5:286-291.

Herner, R.C. 1986. Germination under cold soil conditions. HortScience 21:1118-1122.

Hodges, L. and J.R. Brandle. 1996. Windbreaks: an important component in a plasticulture system. HortTechnology 6:177-181.

Hodges, L., M.N. Suratman, J.R. Brandle, and K.G. Hubbard. 2004. Growth and yield of snap beans as affected by wind protection and microclimate changes due to shelterbelts and planting dates. HortScience 39:966-1004.

Kemp, G.A. 1978. Growth of primary leaves of beans (*Phaseolus vulgaris* L.) under suboptimal temperatures. Can. J. Plant Sci. 58:169-174.

Laing, D.R., P.G. Jones, and J.H.C. Davis. 1984. Common bean (*Phaseolus vulgaris* L.), p. 305-351. In: P.R. Goldsworthy and N.M. Fisher (eds.). The Physiology of Tropical Field Crops. John Wiley and Sons Ltd.

Lamont, W.J., M.R. McGann, M.D. Orzolek, N. Mbugua, B. Dye, and D. Reese. 2002. Design and construction of the Penn State High Tunnel. HortTechnology 12:447-454.

Lamont, W.J., M.D. Orzolek, E.J. Holcomb, K. Demchak, E. Burkhart, L. White, and B. Dye. 2003. Production system for horticultural crops grown in the Penn State high tunnel. HortTechnology 13:358-362.

Marx, E.S., J. Hart, and R.G. Stevens. 1999. Soil test interpretation guide. Cooperative Extension Service, EC 1478, Oregon State University.

Michaelson, G.J. and C.L. Ping. 1989. Interpretation of the phosphorus soil test for Alaska agricultural soils. Agricultural and Forestry Experiment Station, School of Agriculture and Land Resources Management, Circular 66, University of Alaska Fairbanks.

Mullins, C.A. and Straw, R. A. 2001. Performance of filet-type snap bean cultivars in Tennessee. HortTechnology 20:17-19.

Osborne International Seed Company. 2006. Beans - bush beans.22 Mar. 2006. <http://www.osborneseed.com>.

Rainey, K.M. and P. D. Griffiths. 2005. Inheritance of heat tolerance during reproductive development in snap bean (Phaseolus vulgaris L.). J. Amer. Soc. Hort. Sci. 130:700-706.

Sciabarrasi, M.R. and O.S. Wells. 1999. Economic analysis of high tunnel tomato production. Univ. N.H. Coop. Ext. Sept. 1999.

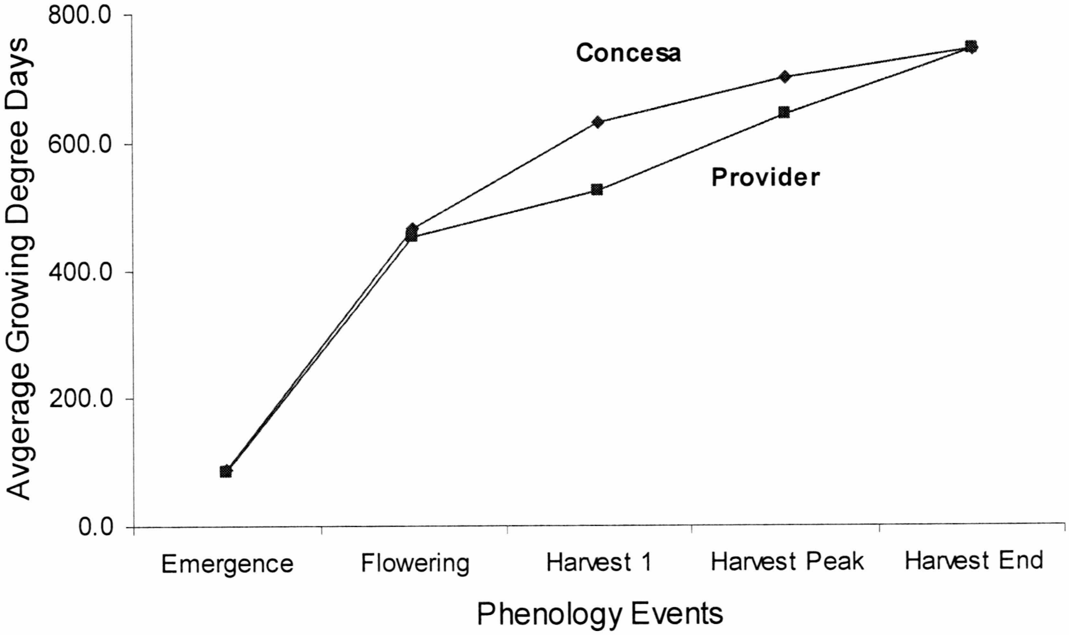
Wagner, P., G. Matheke, and S. Hemshrot. 1989. Recommended vegetable varieties for interior Alaska. Agricultural and Forestry Experiment Station, School of Agriculture and Land Resources Management, University of Alaska Fairbanks. Circular 76.

Wall, J., W.J. Lamont, and M.D. Orzoleck. 2000. Low-technology plastic greenhouses called high tunnels could help farmers extend growing season for many crops. College of Agricultural Science News Release Archive. 5 Oct. 2005. <http://www.aginfo.psu.edu/News/october00/tunnel.html>.

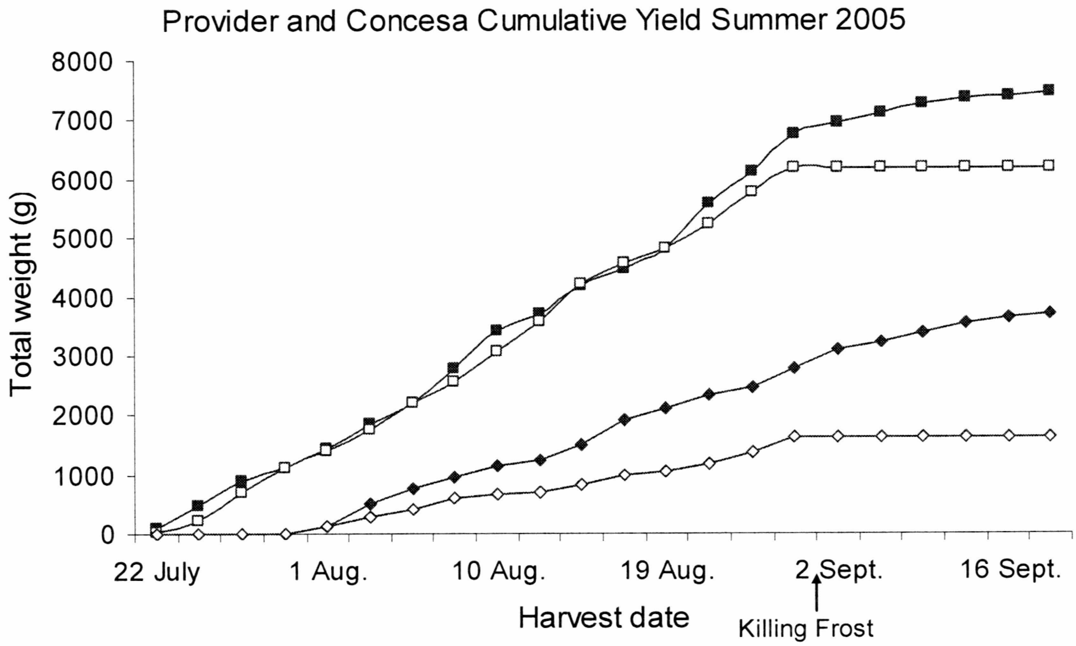
Waterer, D. 2003. Yields and economics of high tunnels for production of warm-season vegetable crops. HortTechnology 13:339-343.

Wells, O.S. and J.B. Loy. 1993. Rowcovers and high tunnels enhance crop production in the Northeastern United States. HortTechnology 3:92-95.

Wells, O.S. 2004. Season extension technology. The American Society of Plasticulture. 14 Oct. 2006. <http://www.plasticulture.org/history_season_extension.htm>.



Fi
g. 3.1. Average Growing Degree Days (GDD) for phenological events, averaged from summer 2005.



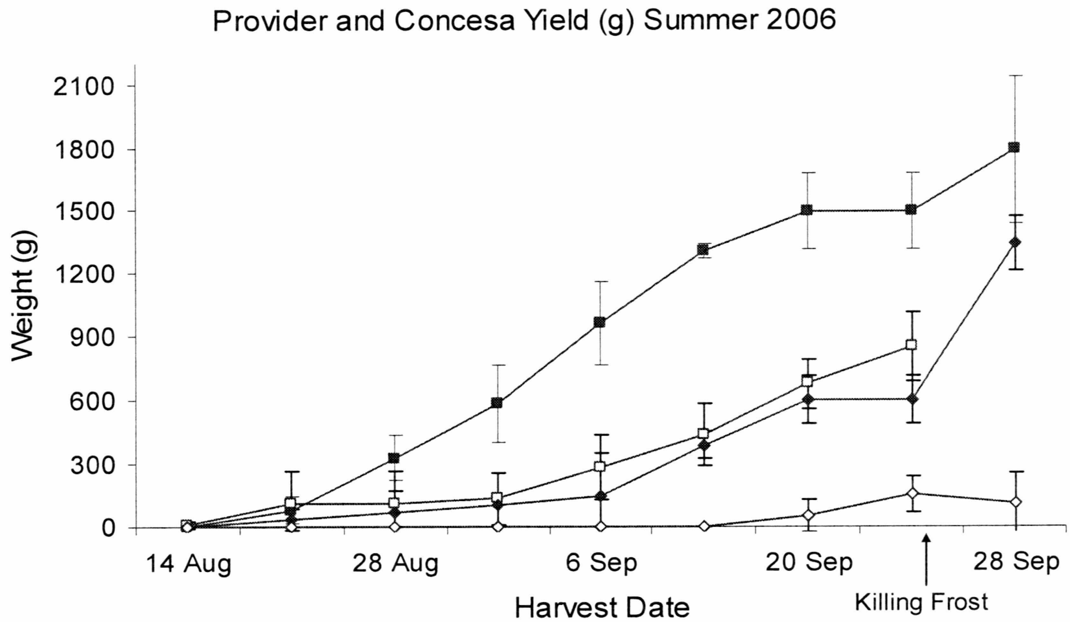
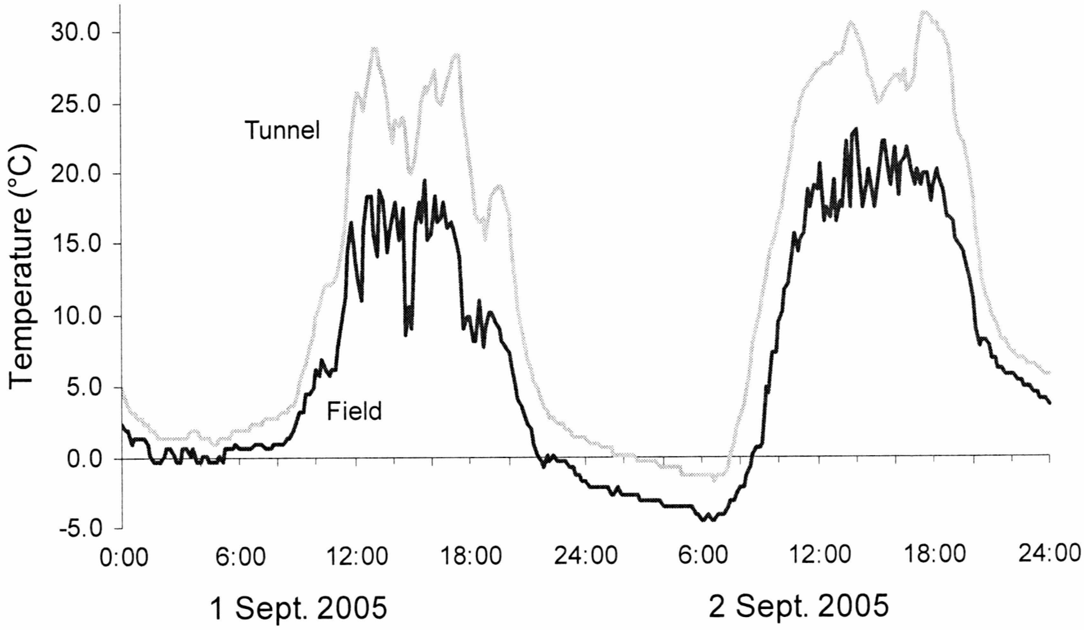


Fig 3.2. Cumulative weight (grams) for three plantings in 2005 and average weight (grams) with standard error bars for two replications in 2006 shown with harvest date. 'Provider' is depicted by squares, 'Concesa' by diamonds and filled symbols indicate the high tunnel while open symbols indicate the open field; 1 g = 0.0353 oz.



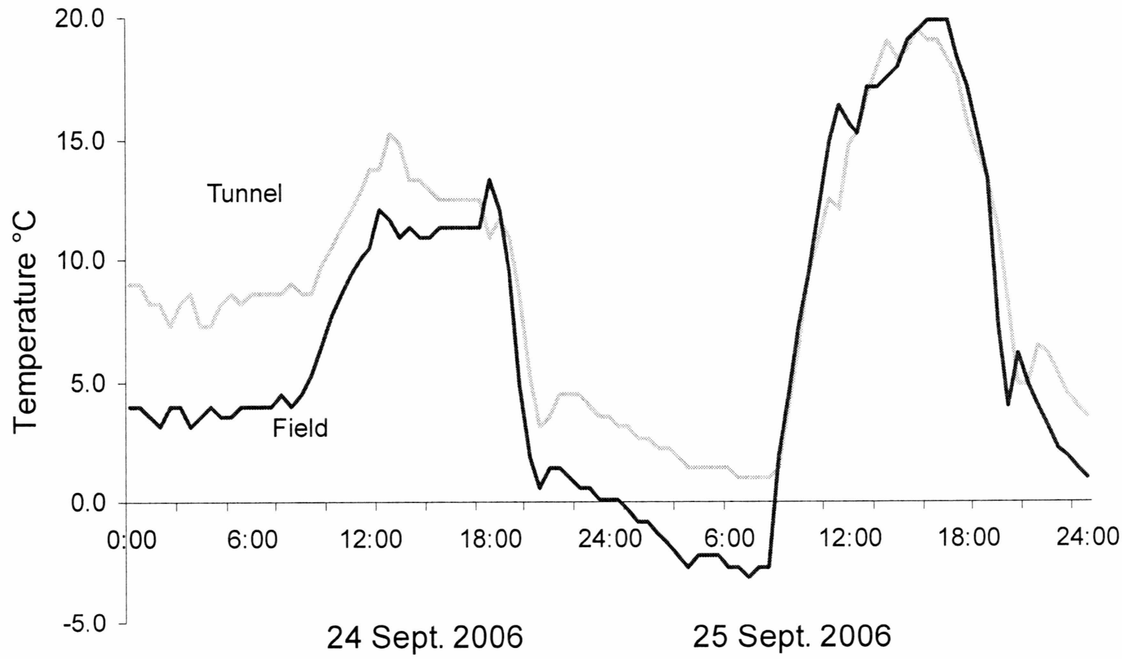


Fig. 3.3. Air temperature recorded every 10 to 30 min, 1 m (3.3 ft.) above ground, in a high tunnel and open field in 2005 and 2006. Measurements were made on 1 and 2 Sept. 2005 and 24 and 25 Sept. 2006; (1.8 x °C) + 32 = °F.

Table 3.1. Frost/freeze dates and length of growing season for summers 2005 and 2006 compared with the historic record.

Frost/Freeze Dates of Occurrence and Length of Growing Season

Growing Season	Last day of occurrence in Spring			First day of Occurrence in Autumn			Length of Freeze-free period (days)		
2005		5 May			2 September			120	
2006		4 June			24 September			112	
Historical	*Earliest*	*Median*	*Latest*	*Earliest*	*Median*	*Latest*	*Longest*	*Median*	*Shortest*
Record[y]	2 May	15 May	28 May	17 Aug.	8 Sept.	27 Sept.	144	115	86

[z](1.8 x °C) + 32 = °F.
[y](Alaska Climate Research Center, 2006b)

Table 3.2. Mean, average low, and average high soil temperatures in a high tunnel and open field. Temperatures were recorded at 15-cm (5.9) soil depth. Temperatures were recorded at 10 to 30 min. intervals and averaged.

	Mean		Low		High	
Month	Tunnel	Field	Tunnel	Field	Tunnel	Field
	Summer 2005 Soil Temperature (°C)[z]					
Late May	14.8	15.7	12.7	13.4	18.5	19.0
June	17.2	17.0	15.0	14.7	20.2	20.2
July	19.6	18.6	17.5	16.5	21.3	20.8
August	16.9	16.1	15.3	14.4	18.6	18.0
1 Sept. to 20 Sept.	11.8	9.2	10.5	7.9	13.2	10.7
25 May to 20 Sept.	16.1	15.3	14.2	13.4	18.4	17.7
	Summer 2006 Soil Temperature (°C)					
Late May	12.7	12.5	11.3	10.6	14.3	14.3
June	14.8	13.6[x]	13.2	11.7	16.6	15.3
July	18.0	15.8	16.5	14.7	19.7	17.4
August	18.0	13.5	16.5	10.2	16.0	14.7
1 Sept. to 20 Sept.	12.9	10.6	11.2	9.3	13.4	11.9
25 May to 20 Sept.	15.1	13.6	13.7	12.2	16.5	15.1

[z](1.8 x °C) + 32 = °F.

[x]1 June to 8 June field soil temperature data was taken from Darleen Masiak at 10 cm.

Table 3.3. Yield characteristics averaged over 2 years for 'Provider' and 'Concesa' snap beans grown inside a high tunnel and in the open field and associated P values for t-test.

Cultivar	Yield ($kg \cdot m^{-2}$) [z]	No. of Mature Pods ($No. \cdot m^{-2}$)
'Provider'		
High Tunnel	2.97 ± 1.03 [y]	494 ± 238
Open Field	2.12 ± 1.45	397 ± 288
P (T<=T) two-tail	0.0740	0.169
'Concesa'		
High Tunnel	1.72 ± 0.52	390 ± 143
Open Field	0.52 ± 0.54	130 ± 149
P (T<=T) two-tail	0.00243	0.000204

[z] 1.00 $kg \cdot m^{-2}$ = 0.204 $lb. \cdot ft.^{-2}$, 1.0 kg =2.20 lb.

[y] Values represent the standard deviation in means over site years. Summer 2005 n = 3, summer 2006 n = 2.

Table 3.4. Monthly and cumulative growing degree days [base 10 °C (50 °F); max 30 °C (86 °F] for summer 2005 and 2006. Chill hours [base 0 °C (32 °F); max 10 °C] for Summer 2006 only.

	Growing Degree Days (GDD) Air Temperature (°C)^{z}				*Chill Hours (CH) Temperature (°C)*^{z}	
	Summer 2005		Summer 2006		Summer 2006	
Month	Tunnel	Field	Tunnel	Field	Tunnel	Field
25 May to 31 May	70.8	67	44.8	60.8	30.5	25.5
June	275.5	255.5	240.1	264	95.5	91.5
July	309.2	299.4	260.6	280.6	33.5	40.5
August	275.5	255.3	217.6^{x}	222.9^{y}	154.5	208
1 Sept. to 20 Sept.	144.7	99.5	124.6	142	NA	NA
September	124.6	142	164.8	178.4	306.5	383
25 May to 20 Sept.	1065.4	976.7	887.6	968.1	NA	NA
25 May to 30 Sept.	ND	ND	922.9	982.8	611.5	738.5

^{z}(1.8 x °C) + 32 = °F.

^{y}A temporary heat source was put in the high tunnel 23 Aug.

^{x}Plots in the open field were covered with floating Reemay frost cloth covers.

Chapter 4 Conclusion

Summary

High tunnels efficiently and inexpensively improved crop production in an area with a short growing season and unpredictable temperatures. Warm and cool season crops were grown in the high tunnel at UAF in 2005 and 2006 with general success, as has been the case elsewhere in the U.S. Economic analyses that contrast high tunnels with low tunnels, and traditional field cultivation suggest improvements in yield and quality from high tunnels may compensate for additional costs within one year. High tunnel size, management, and crop and cultivar selection, are important consideration in maximizing productivity and profitability. In spite of some additional cost and management considerations, high tunnels can contribute to an economically viable farm through diversification, reliability, and yield improvements.

High Tunnel Crop Production

Along with snap beans and lettuce, we grew a variety of other high value, warm-season crops in the high tunnel. In 2005: tomatoes (*Lycopersicon esculentum*); summer squash (*Cucurbita pepo*); basil (*Ocimum basilicum* L.); and in 2006: tomatoes; bell peppers (*Capsicum annuum*); and strawberries (*Fragaria*×*ananassa* Duch.). Although yield was not recorded for all crops, visually, high tunnel crops were protected from frost and cold injury compared with field grown crops (personal observation). For example, tomato plants in the middle of the tunnel had noticeably greater height, yield, and better appearance than plants near tunnel ends where cold penetration was greater. In general, warm season crops seemed to perform better in the tunnel compared with the field, although it varied with climactic conditions, cultivar, and crop type.

'Provider' produced an average of 1.01 lb./ft. of row space inside the high tunnel. At a price of $4.50·lb.$^{-1}$ (G. Kerndt, personal communication), in a 14 × 96 ft. high tunnel, in one season it might be possible to produce 339 lb. if there were two successional plantings. The cropping space could be used for greens early or planted again with snap beans after peak harvest was achieved, depending on the growing season. Using Sciabarrasi and Wells (1999) (Appendix A) economic analyses but eliminating tomato specific labor such as staking and pruning for our yield rates, there would be a net loss of $102.25. Semi-indeterminate varieties (compared with determinate as we used) may produce greater yields for the given row space. Less ventilation may also be a way to improve yields by increasing GDD enough to decrease maturity times and improve yields sufficiently to offset costs. As high tunnels did not increase yields of either leaf or romaine lettuce consistently, economic analyses were not done and it was inferred that using high tunnels for head lettuce of 'Two Star' and 'Parris Island cos' would not be profitable.

Recommendations and Management Concerns

Depending on management choices, high tunnel ventilation could be a twice-daily task. Wells (2004) recommends morning ventilation to reduce humidity and control excessively high temperatures; and closing the high tunnel at night for heat retention. Less frequent manual ventilation may significantly cut down labor costs and may even improve growth depending on crop type and phenological stage. An inexpensive motor with a temperature sensor to open the sides might also cut down on labor costs and be more effective for maintaining a more narrow range of temperatures.

In 2005, no additional heat source was used, while in 2006, a monitor heater was used in the fall set to 7 °C at night. High tunnel plants evaded frost damage with and without additional heat whereas field plants were desiccated. Although 2005 tunnel plants did not senesce with the first frost, they did sustain visible cold injuries. In summer 2006, snap beans, tomatoes, and bell peppers were healthy after the first frost with additional heat. Using Reemay was observed as an additional way to prevent cold injury without additional heat.

Soil tests suggested a divergence in soil fertility after one summer of production. Available potassium (K) was lower in the tunnel compared with the field from autumn 2005 to autumn 2006. Fertigation may be an important way to supply adequate nutrition without precipitation for mineralization. Soluble salt (Electric Conductivity: EC) levels in the tunnel were rising faster than in the field. EC levels of 0.9 to 1.0 mmhos·cm^{-1} may even be of concern (Burkhart, 2003). If salt levels continued to rise in the high tunnel, leaching with low sodium water, gypsum applications, or rotation of the high tunnel may be necessary. A sprinkler irrigation system may be an important way to decrease salt build-up.

In some situations, the rain shelter effect of the high tunnel could be beneficial by preventing excess leaching of nutrients into ground water and limiting overall nutrient loss. However, the effect may prevent adequate mineralization of water insoluble fertilizers. Fertigation, or soluble fertilizer application via drip irrigation, may be more efficient in providing adequate nutrition for tunnel crops (Burkhart, 2003) and is not contingent on rainfall for mineralization. Compost applications in high tunnels should be monitored more closely compared with field applications because of potential salt build-up resulting from lack of leaching and slow mineralization.

Further Research Objectives

Continued research on crops, cultivars, and management practices will contribute to successful high tunnel production in Alaska's unique growing environment. A better understanding of the economics surrounding high tunnel production and market demand would be useful for local farmers. It is likely that specialty markets that require higher quality, cleaner, reliable produce will be a good outlet for high tunnel production. It is also important to evaluate the pros and cons of different management strategies both economically and for productivity. Direct seeding options may also lower costs if it could eliminate the need for transplanting.

High tunnels are a lower risk, and lower capital investment than conventional greenhouses, and can be a more practical entry into commercial vegetable and fruit production for growers. For example, a young grower in Pennsylvania bought a 17 × 96 ft. high tunnel to produce tomatoes and paid for it in one year (Lamont et al., 2002). Although high tunnels are not as reliable as an automated greenhouse, with attentiveness to ventilation and some additional heat, they are more dependable than low tunnels and open field production.

Opportunities to expand and extend local production of warm season crops such as snap beans, tomatoes, bell peppers, cucumbers, and basil may exist for the Fairbanks area (personal observation). With a short growing season and unpredictable frosts, relative isolation, and a local willingness to pay for fresh produce, there seems to be sufficient demand for high tunnel production of a variety of vegetables in the Tanana Valley. Continued research on crops, cultivars, and management practices will contribute to successful high tunnel production in Alaska's unique growing environment.

Literature Cited

Burkhart, E.P. 2003. High tunnel nutrient management: Fertilizers, composts, and cover crops, p. 82-102. In: W. Lamont, M. Orzolek, and L. White (eds.) High tunnel production manual. Center for Plasticulture, Department of Horticulture, College of Agriculture, Pennsylvania State University.

Lamont, W.J., M.D. Orzolek, J. Holcomb, R.M. Crassweller, K. Demchak, E. Burkhart, L. White, and B. Dye. 2002. Penn State high tunnel extension program. HortTechnology 12(4):732-735.

Sciabarrasi, M. R. and O. S. Wells. 1999. Economic analysis of high tunnel tomato production. University New Hampshire, Coop. Ext. Fact Sheet. 22 Oct. 2006. <http://www.plasticulture.org/history_season_extension.htm>.

Wells, O.S. 2004. Season extension technology. American Society of Plasticulture, University of New Hampshire. 22 Oct. 2006. <http://www.plasticulture.org/history_season_extension.htm>.

Appendix A Economic Analysis of High Tunnel Tomato Production

Economic Analysis of High Tunnel Tomato Production
(one tunnel, 14' x 96' = 1,344 sq. ft.)

Annual Returns and Expenses

	Amount or Rate		Price or Charge		Dollars	
I. Receipts	3,000	pounds	$2.00	per pound		**$6,000.00**
II. Marketing Costs			25%	of price received		**$1,500.00**
III. Production Expenses						
A. Plants	240	plants	$0.20	each	$48.00	
B. Stakes	128	stakes	$0.30	each	38.40	
C. String	2,500	feet	$17.00	tunnel	17.00	
D. Fertilizer & lime, preplant			$6.00	tunnel	6.00	
E. Fertilizer through trickle irrigation			$22.00	tunnel	22.00	
F. Pest control, *Encarsia formosa*			$30.00	tunnel	30.00	
G. Basket Replacement	5	baskets	$3.50	each	17.50	
H. Labor	111.5	hours	$11.00	per hour		
	4.0	hrs. for preplant preparation			44.00	
	15.0	hrs. to plant, set stakes & stringing			165.00	
	25.0	hrs. to prune, control pests & ventilate			275.00	
	17.5	hrs. to irrigate & fertigate			192.50	
	40.0	hrs. to harvest (four times)			440.00	
	10.0	hrs. for annual maintenance & cleanup			110.00	
I. Miscellaneous variable costs (rototiller & injector)			$15.00	tunnel	15.00	
J. Operating interest	$240	dollars	10%	interest	24.00	
Total Variable Production Expenses (sum of A through J)						**$1,444.40**
K. Annual depreciation (zero salvage value)						
Structure	$1,860	investment	10	years	$186.00	
Plastic	$259	investment	3	years	86.33	
L. Annual interest charge on investment						
Structure	$930	avg. investmen	10%	interest	93.00	
Plastic	$130	avg. invest.	10%	interest	12.95	
M. Land costs						
Interest	$420	investment	6%	interest	25.20	
Real estate tax (share)			$15.00	tunnel	15.00	
N. Other fixed costs (equip. & machine related)			$60.00	tunnel	60.00	
Total Fixed Production Expenses (sum of K through N)						**$478.49**
IV. Annual Net Returns (receipts less marketing costs less production expenses)						**$2,577.11**

V. Annual Net Returns for Different Prices and Production (marketing cost kept at $.50 per pound; net returns adjusted by $.15 per pound harvest cost.)

		Prices Received per Pound				
		$1.50	$1.75	$2.00	$2.25	$2.50
Pounds Produced	2,500	$652	$1,277	$1,902	$2,527	$3,152
	2,750	$865	$1,552	$2,240	$2,927	$3,615
	3,000	$1,077	$1,827	$2,577	$3,327	$4,077
	3,250	$1,290	$2,102	$2,915	$3,727	$4,540
	3,500	$1,502	$2,377	$3,252	$4,127	$5,002

by Michael R. Sciabarrasi and Otho S. Wells, Extension Specialists, University of New Hampshire Cooperative Extension, September 1999.

Appendix B Soil Analyses (0 to 15 cm) 2005 to 2006

6 May 2005

Air Dry	1:1	mmhos	ppm	ppm	M3 ppm	ppm	ppm	ppm	ppm
	pH	E.C.	NH_4^+-N	NO_3^--N	P	Cu	Zn	Mn	Fe
Field	6.25	0.76	1	25	188	4.8	10.6	19.7	418
High Tunnel	6.27	0.60	1	18	198	4.5	10.6	19.9	428

100 °C Oven Dry	meq/100g CEC
Field	28.00
High Tunnel	30.86

13 Sept. 2005

Air Dry	1:1	mmhos	ppm	ppm	M3 ppm	ppm	ppm	ppm	ppm	ppm	meq/100g	meq/100g	meq/100g	meq/100g	meq/100g
	pH	E.C.	NH_4^+-N	NO_3^--N	P	Cu	Zn	Mn	Fe	S	K	Ca	Mg	Na	CEC
Field Beans	7.01	0.50	2	5	259	5.4	12.8	40.1	380	24.9	0.74	26.47	6.40	0.24	30.20
Field Lettuce	6.71	0.50	2	12	220	5.2	9.6	35.4	378	19.7	0.66	25.82	6.62	0.27	30.36
High Tunnel Beans	7.29	0.52	2	4	131	6.0	8.2	21.6	376	26.3	0.19	32.10	7.76	0.31	33.57
High Tunnel Lettuce	7.10	0.62	2	15	174	5.7	8.4	23.3	379	27.7	0.18	29.68	7.46	0.35	34.49

100 °C Oven Dry	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	meq/100g	meq/100g	meq/100g	meq/100g	meq/100g
	NH_4^+-N	NO_3^--N	P	Cu	Zn	Mn	Fe	S	K	Ca	Mg	Na	CEC
Field Beans	2	5	264	6	13	41	387	25.4	0.76	26.97	6.52	0.24	30.77
Field Lettuce	2	12	224	5	10	36	385	20.1	0.68	26.31	6.75	0.28	30.94
High Tunnel Beans	2	4	134	6.1	8.4	22.1	384	26.9	0.19	42.78	7.92	0.32	34.27
High Tunnel Lettuce	2	15	178	5.8	8.6	23.8	387	28.3	0.18	30.30	7.62	0.35	35.21

21 May 2006

M3

Air Dry	1:1	mmhos	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	%	%
	pH	E.C.	NH^+_4-N	NO^-_3-N	P	Cu	Zn	Mn	Fe	S	K	Ca	Mg	Na	CEC	C	N
High Tunnel	6.68	1.13	3	31	194	5.2	9.1	28.3	428	32.6	0.20	28.80	7.51	0.39	29.29	4.65	0.35
Field	7.04	0.68	3	14	288	6.0	16.3	43.2	423	20.3	0.65	24.54	6.27	0.23	24.20	4.58	0.38

M3

100 °C Oven Dry	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	%	%
	NH^+_4-N	NO^-_3-N	P	Cu	Zn	Mn	Fe	S	K	Ca	Mg	Na	CEC	C	N
High Tunnel	3	32	199	5	9	29	439	33.4	0.20	29.55	7.71	0.40	30.05	4.77	0.36
Field	3	14	295	6	17	44	433	20.8	0.66	25.11	6.41	0.23	24.76	4.69	0.39

4 Oct. 2006

M3

Air Dry	1:1	mmhos	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	%	%
	pH	E.C.	NH^+_4-N	NO^-_3-N	P	Cu	Zn	Mn	Fe	S	K	Ca	Mg	Na	CEC	C	N
High Tunnel	7.20	1.26	3	34	300	4.8	9.2	30.1	442	37.1	0.33	31.28	7.70	0.27	28.35	4.89	0.36
Field	6.98	0.72	3	10	329	4.5	8.7	38.4	434	24.7	0.88	29.19	7.82	0.29	27.46	5.16	0.40

M3

100 °C Oven Dry	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	meq/ 100g	%	%
	NH^+_4-N	NO^-_3-N	P	Cu	Zn	Mn	Fe	S	K	Ca	Mg	Na	CEC	C	N
High Tunnel	3	35	309	5	9	31	455	38.2	0.34	32.22	7.93	0.28	29.20	5.04	0.37
Field	3	10	339	5	9	40	447	25.5	0.91	30.06	8.06	0.30	28.28	5.31	0.41